

# PROCESSING AT1M DATA

Processing from Raw Data Files to Free Air Gravity  
Disturbance

## ABSTRACT

Introduction to the processing of AT1M files to obtain the Free Air Gravity Anomaly data. Includes MATLAB processing scripts and a survey case study.

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## 1. Introduction

This document is intended to guide the AT1M marine gravity meter user through the processing of the raw gravity data recorded by the meter to obtain the processed Free Air Anomaly gravity results.

The AT1M sensor is a scalar (full field) gravity sensor mounted in a gyroscopically stabilized platform that keeps the sensitive (vertical) axis of the gravity meter aligned with the local gravity vector. Only the magnitude of this vector is recorded in the data file.

The instrument output corresponds to the changing gravitational force acting on the sensitive axis of the instrument as it moves horizontally across the earth's surface. All the kinematic effects, as well as drift, need to be removed from the measurement to get the most accurate result. In most marine surveys, the vertical accelerations can be disregarded because the average vertical position is constant when the data is filtered with relatively long filter times. Therefore, the only kinematic correction that needs to be applied is the Eötvös correction. When the Eötvös correction is calculated using the position from an external file, a very important consideration is the synchronization between the gravity data and the GPS position data.

The gravity meter is maintained in the level position by a 2-axis gyro stabilized platform. The platform uses only the accelerometers outputs, and each axis behaves as if the gravity meter is hanging from a pendulum with either a 4-minute, for standard, or an 8-minute period for the long platform setting. The platform attenuates the tilt of the gravity meter when the ship changes velocity or heading. If the ship is traveling at constant speed in a straight line or turning with a large radius, the gravity meter will be aligned with the local gravity level vector and no off-level correction will be necessary.

The AT1M sensor has very small cross coupling effects, however, the gravity output can be smoothed by applying a cross coupling correction. The main cross coupling correction is the VE correction. The gravity meter output signal, QC Gravity (Quality Control Gravity), is already corrected for cross couplings if the cross-coupling gains have been entered in the configuration file.

## 2. Processing of AT1M Marine Gravity Data

The following diagram shows a simplified data flow of the basic processing of the AT1M gravity data, when using the positions recorded by the GPS in the data file.

The FFG is the full field gravity and FAA is the free air anomaly. Eötvös Corrections and Normal Gravity are calculated using the geodetic positions stored in the data file

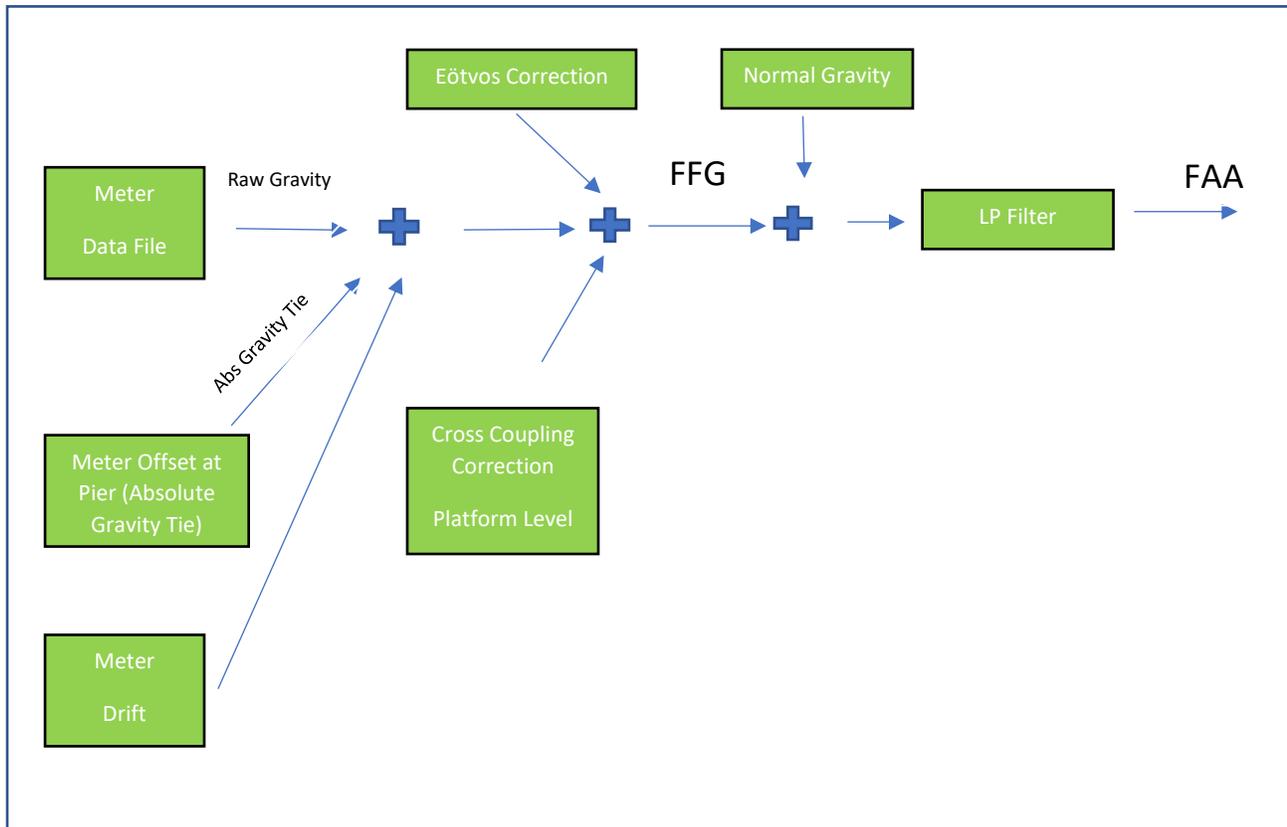


Figure 2.0.1 Simplified Processing Data Flow

The meter drift rate can be obtained by re-occupying the same location multiple times, or it can be removed by minimizing the crossing point mis-ties.

The cross-coupling correction can be performed using the coefficients stored in the meter or recalculated using cross correlation technique, or by minimization of the crossing point mis-ties.

## 2.1 Main Gravity Processing Equation

The output of the gravity meter is the specific force acting on the sensitive axis of the instrument. Since we are only interested in the gravity part, all kinematic effects need to be removed from the measurement.

In most marine surveys, the vertical accelerations can be neglected because the average vertical position tends to be constant when the data is filtered with relatively long filter times. In some surveys the effect of variation in sea levels due to wind and ocean currents as well as temperature and density effects, may need to be accounted for.

In most cases, the only kinematic correction that needs to be applied is the Eötvös correction. When the Eötvös correction is calculated using the position from an external file, an important consideration is the synchronization between the gravity data and GPS position data.

Full field gravity

$$FF_g = g_M + \delta Eötvös + \partial Tilt + CC + gDrift + gOffset + Tidal \quad (2.1.1)$$

Free Air gravity

$$F_{AA} = g_M + \delta Eötvös + \partial Tilt + CC + gDrift + gOffset + Tidal - g_{norm} \quad (2.1.2)$$

The obtained  $g_{FA}$  in marine applications will contain high frequency high amplitude noise generated by the sea motions of the ship. This signal is usually eliminated using a very low stop frequency low pass filter or Kalman smoother. Typical noise levels added to the signal are in the range of 10,000 to 60,000 milliGals (mGals).

Equations 2.1.1 and 2.1.2 deal only with the vertical component of gravity and corrections. The main output measurement of the gravity meter is  $g_M$ , which is the specific force measured by the sensor and is calibrated in mGals.

$g_{FF}$  = Full field gravity mGals

$g_M$  = Output of the gravity meter mGals. [Data file column \[2\] Gravity](#)

(Needs a 4 seconds time shift with respect to the time stamp on the data)

$\delta Eötvös$  = Correction for the vertical components of Coriolis and centripetal accelerations

$\partial Tilt$  = Correction for platform verticality.

$CC$  = Dynamical cross coupling

$gDrift$  = Gravity meter drift compensation

$gOffset$  = Gravity meter offset to the absolute gravity benchmark tie-in (normally done with a land gravity meter and vertical measurements of the location of the sensor on the ship to the dock).

$Tidal$  = Tidal gravity compensation.

## 2.2 Eötvös Correction

During marine gravity surveys the gravity data are acquired on a moving platform. Thus, the centrifugal force acting on the gravity sensor is different from when the meter is stationary. Any eastward component of the velocity adds to the velocity of the rotation of the earth thus decreasing the specific force measured by the sensor. A westward component does the opposite. In addition to these effects, a northward direction creates a new component of centrifugal force. All these effects added together are called the Eötvös correction. The formulae are given in many geophysical text books. The following are the ones in Telford et al (1990) often used for marine gravity processing applications:

$$\delta E_{\text{ötvös}} = 4.04 \cdot |V| \cdot \cos \phi \cdot \sin \alpha + 0.001211V^2 \quad V=\text{Km/h} \quad (2.2.1)$$

$$\delta E_{\text{ötvös}} = 7.503 \cdot |V| \cdot \cos \phi \cdot \sin \alpha + 0.004154V^2 \quad V=\text{Knots/h} \quad (2.2.2)$$

where:  $\alpha$  and  $\phi$  are the course heading relative to north and the latitudes. The final unit of the correction for both equations is milliGals.

A more complete formula suitable for airborne applications, or marine use if the ellipsoidal height is set to zero, uses the equation described by Harlan 1968 "Eötvös corrections for Airborne Gravimetry" JGR 73, n14.

$$\delta E_{\text{ötvös}} = \frac{V_N^2}{a} \left[ 1 - \frac{H}{a} + f [2 - 3 \sin^2(\phi)] \right] + \frac{V_E^2}{a} \left[ 1 - \frac{H}{a} - f \sin^2(\phi) \right] + 2 w V_E \cos(\phi) \quad (2.2.3)$$

### A) Using Speed, Course and Latitude stored in the data file

The calculations for the Eötvös correction can be performed using the GPS data stored in the data files columns 17, 18 and 15.

$V$  = velocity Knots/h. [Data file \[17\] Speed in knots](#)

$\phi$  = north heading [Data file \[18\] Course in degrees](#)

$\delta$  = Latitude [Data file \[15\] Latitude in decimal degrees](#)

### B) Using Speed, Course and Latitude stored in an external file

Alternatively, the GPS geodetic coordinates needed for the Eötvös calculation can be supplied by an external file. In this case it is important that the two files are very well time synchronized.

### C) Using Latitude and Longitude from and External position File

When using Latitude and longitude positions from and external file the North and East velocities can be calculated using the equations from sections 3 and 4.

Method A is the most preferred case. In this case we know that the Eötvös correction is well synchronized with the gravity meter sensor output. In some cases, the installation does not allow the use of a NMEA string position in real time, and the position data used for the processing comes from an external file. For this case it is important that Gravity and GPS data are properly time synchronized.

## 2.3 Platform Tilt Correction

The tilt correction is only necessary when the ship is experiencing significant changes in velocity or heading during the normal gravity acquisition. To determine if the platform level compensation is needed, the data can be processed without applying any compensation, calculating the compensation using equation 2.3.7. In this way we can estimate this tilt contribution to the final processed data. A trade off of applying this correction is that the any errors in GPS position would add some noise in the data if the compensation is used.

Different methods can be used for correcting the platform tilts generated by the speed or heading of the ship. It is important to know that this correction due to the quadratic terms, can generate bias in the correction when the reading of the acceleration contains noise. Special care must be taken in using a good quality GPS position, for instance using INS system or differential GPS. The method is simple to calculate and get a good correction for most of cases. The other compensation equation has been included for completeness. A more extended explanation of these out of level correction techniques can be found in reference [1].

$a_x$  = cross accelerometer (mGal). *Data file [3] Long accelerometer\*1000*

$a_y$  = long accelerometer (mGal) . *Data file [4] cross accelerometer\*1000*

$am_x$  = cross calculated acceleration from GPS (mGal). *Calculated from GPS section 2 and 3*

$am_y$  = long calculated acceleration from GPS (mGal). *Calculated from GPS sections 2 and 3*

$A_E$  = East acceleration (mGal) *Calculated from GPS, sections 2 and 3*

$A_N$  = North acceleration (mGal) *Calculated from GPS sections 2 and 3*

$g$  = 980000 (mGal)

$\partial Tilt$  = gravity correction (mGal)

$\phi_x, \phi_y$  Cross and long tilt angles

### Method 1

Peters and Brozena, trigonometric, see reference [1] for more details:

$$\phi_y = -(g + \sqrt{g^2 + 2a_y(a_y - am_y)})/a_y \quad (2.3.1)$$

$$\phi_x = -(g + \sqrt{g^2 + 2a_x(a_x - am_x)})/a_x \quad (2.3.2)$$

$$\partial_y = \frac{g\phi_y^2}{2} - a_y\phi_y \quad (2.3.3)$$

$$\partial_x = \frac{g\phi_x^2}{2} - a_x\phi_x \quad (2.3.4)$$

$$\partial Tilt = \partial_y + \partial_x \quad (2.3.5)$$

### Method 2

Peters & Brozena direct:

$$\partial Tilt = \sqrt{a_x^2 + a_y^2 + g^2 - A_E^2 - A_N^2} - g \sim \frac{a_x^2 + a_y^2 - A_E^2 - A_N^2}{2g} \quad (2.3.6)$$

### Method 3

Another bias free tilt compensation is based on the projection of the full gravity and horizontal accelerations into the sensitive axis of the gravity meter.

$$\partial Tilt = (1 - \cos(\phi_x) \cos(\phi_y)) g + \sin(\phi_x) * a_x + \sin(\phi_x) \cos(\phi_x) a_y \quad (2.3.7)$$

Where the platform tilt angles can be approximated by the fact the tangent of an angle tends to the angle itself for small angles.

With  $a_x$  and  $a_y$  been the GPS derived cross a long acceleration, and  $x_{acc}$  and  $l_{acc}$  the meter accelerometer reading for the cross and long axis.

For a perfectly calibrated accelerometers and a GPS calculated acceleration free of noise, the difference of  $a_x - x_{acc}$  should be zero when the platform is level. If the difference is different, this value corresponds to the coupling of the full g in the sensitive axis off the accelerometer.

$$\phi_x \approx \frac{a_x - x_{acc}}{g} \quad (2.3.8)$$

$$\phi_y \approx \frac{a_y - l_{acc}}{g} \quad (2.3.9)$$

Where the angles  $\phi_x$  and  $\phi_y$  are in radians.

It is important to filter some the accelerometer and GPS derived accelerations before calculating the error angle, since the high frequency noise generated from the GPS derived accelerations can generate a high frequency noise on the error angle, which will be then rectified by the nonlinear characteristic of the sinus and cosines trigonometric functions.

## 2.4 Cross Coupling Corrections

Most of accelerometers and gravity meter present variations of the output with the motions and acceleration in other than the sensitive axis, and sensitivity to vibrations.

The DGS AT1M sensor has much smaller cross coupling than other beam-based gravity meters due to the fact that the beam keeps lock in position by the electronic feedback. In any case the final quality of the output of the gravity meter can be improved. The amount of improvement of the data depend in the sea conditions, and size of the ship.

### Cross correlation method for finding the cross-coupling factors AT1M shipboard gravity data

- 1) Filter Eötvös corrected gravity and all the cross-coupling channels with at least with a filter length in the range 100 to 300 seconds
- 2) Perform a double derivation of all the channels and Eötvös corrected gravity. Since we are only solving for the curvature.

*Important: Note that all the terms used on equation (3.4.1) have to be double differenced for instance using a Tylor expansion derivative or any other technique.*

When applying this cross-correlation solution, be sure to include lines in all directions at least, and better with multiple directions to minimize the correlation between the channels (monitors)

Find the gains cross coupling correction gains G by solving the curvature equations:

$$-\ddot{g} = G_1 \ddot{v}e + G_2 \ddot{v}cc + G_3 \ddot{a}l + G_4 \ddot{a}x \quad (2.4.1)$$

Where g is Eötvös corrected gravity. File data [2] Gravity-calculated Eötvös corrections

Ve= [Data file \[11\] monitor VE](#)

Vcc=[Data file \[12\] monitor VCC](#)

Al=[Data file \[13\] monitor AL](#)

Ax= [Data file \[14\] monitor AX](#)

Once the optimum cross coupling gains have been found  $G_1 \dots G_4$ , each gain is multiplied by the respective Data file recorded monitor to compute the cross-coupling correction

$$CC = G_1 ve + G_2 vcc + G_3 al + G_4 ax \quad (2.4.2)$$

## 2.5 Gravity Meter Drift Correction

Gravity drift is inherited by the spring-mass system. It may be caused by temperature change, elastic aging, and hysteresis of the system, etc. The drift rate is usually higher for new meters and usually gets better with time as the system matures. The drift rate can be obtained by occupation of the same special points (stations).

$$Drift = (g(t_1) - g(t_2)) / (t_2 - t_1) \quad (2.5.1)$$

Once the Drift rate is known the survey data can be corrected by

$$gDrift = Drift (t - t_0) \quad (2.5.2)$$

In general, the gDrift correction is very small for AT1M meters. Typical values of drift rates for an AT1M sensor are 1 to 3 mGals/month.

## 2.6 Gravity Meter Offset Correction

The AT1M sensors are calibrated to have a relative accuracy. That is, the difference between two gravity values in two different locations will be the same as that which we would measure using an absolute gravity meter. The offset of the calibration is an arbitrary number, since due to the gravity meter drift it would change with time.

During the processing of the gravity meter data, it may be required to convert the gravity readings to full field gravity (absolute measurement), in order to be able to subtract the theoretical gravity (gravity normal) for each data point corresponding to each position and therefore obtain the FAA free air anomaly.

The output of the gravity meter can be adjusted to obtain an absolute gravity value by measuring the gravity in a location (Gravity Tie) where the full value of g is known.

$$gOffset = gTie - gAT1M \quad (2.6.1)$$

## 2.7 Tidal Correction

The tidal correction refers to the deformation caused by the moon-sun gravitational pull on the earth. The deformation can be up to about 10 cm. Tidal correction compensates for gravity effects caused by the attraction of the moon and the sun and the deformation of the earth which it produces. The tidal correction causes a periodic (12 hour) gravity change which can reach a maximum peak to peak value of 300  $\mu$ Gals. For geophysical surveys the earth tide is usually not considered useful information and removed from the data. Fortunately, the earth tide can be predicted and corrected for to an accuracy of 1 to 3  $\mu$ Gals.

## 2.8 Normal Gravity

The normal gravity is the gravity caused by a reference ellipsoid with a uniform density. The reference ellipsoid best fits the geoid of the earth (the difference between these two seldom exceeds 50m). The shape of the reference ellipsoid was first investigated by measuring the arc length of degrees at various latitudes. The reference ellipsoid is symmetric through its center and about the axis of rotation. It is a mathematical model and can be described by two parameters: its equatorial radius  $a$  and polar radius  $b$ . These two parameters are often expressed in terms of the flattening:

$$f = \frac{a - b}{a} \quad (2.8.1)$$

The closed-form expression of the normal gravity (Somigliana equation) is given as:

$$g_{norm} = g_e \frac{(1 + k \cdot \sin^2 \phi)}{\sqrt{1 - e^2 \cdot \sin^2 \phi}} \quad (2.8.2)$$

where  $k$  is the normal gravity constant;  $\phi$  is the latitude and  $g_e$  is the gravity at equator.

There are three different reference ellipsoids in use to compute the normal gravity. These ellipsoids are defined and refined by international agreement through the International Union of Geodesy (IAG) and its umbrella organization, the International Union of Geodesy and Geophysics (IUGG). The first reference ellipsoid was established in 1930 and the 30's formula is expressed as:

$$g_{norm} = 9.78049(1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi) \text{ m/sec}^2 \quad (2.8.3)$$

The satellite data provided far more accurate geodetic parameters and a new ellipsoid was defined in 1967 and was called the Geodetic Reference System 1967 (GRS67). The most recent is the Geodetic Reference System 1980 (GRS80), which led to World Geodetic System 1984 (WGS84).

The parameters used in the closed-form expressions for GRS67 and GRS80 are in the table below:

	GRS67	GRS80
$g_{norm}(\text{m/sec}^2)$	9.7803184558	9.7803267715
$K$	0.001931663383	0.001931851353
$E^2$	0.00669460532856	0.00669438002290

Unsurprisingly, the 1930, 1967 and 1980 normal gravity formulas produce different normal gravity values. For instance, at latitude 45, the difference between the 1930 and 1967 formulae is more than 10 milliGals. The difference, when compared with the 1980's formula, is about 9 mGals. The differences between the 1967 and 1980 solutions are less than 1mGal. It is usually a good idea to use the most current formula for your gravity reduction. Also, if you have to deal with data acquired in the early days and wish to merge them with your newly collected data, make sure that all the data sets use the same normal gravity correction.

The normal gravity correction is also referred to as the latitude correction. Its computation comprises two parts: the gravitational attraction of the mass and the centrifugal force due to the rotation of the earth. And these two values change solely with the latitude -- gravity is the lowest at the equator because of the bigger distance from the center of the earth and the centrifugal force; it is the highest at the poles for the opposite reason. Using the 1980 formula, we know that the normal gravity increases about 5185.959 mGal when moving from equator to the pole, (figure 2 below).

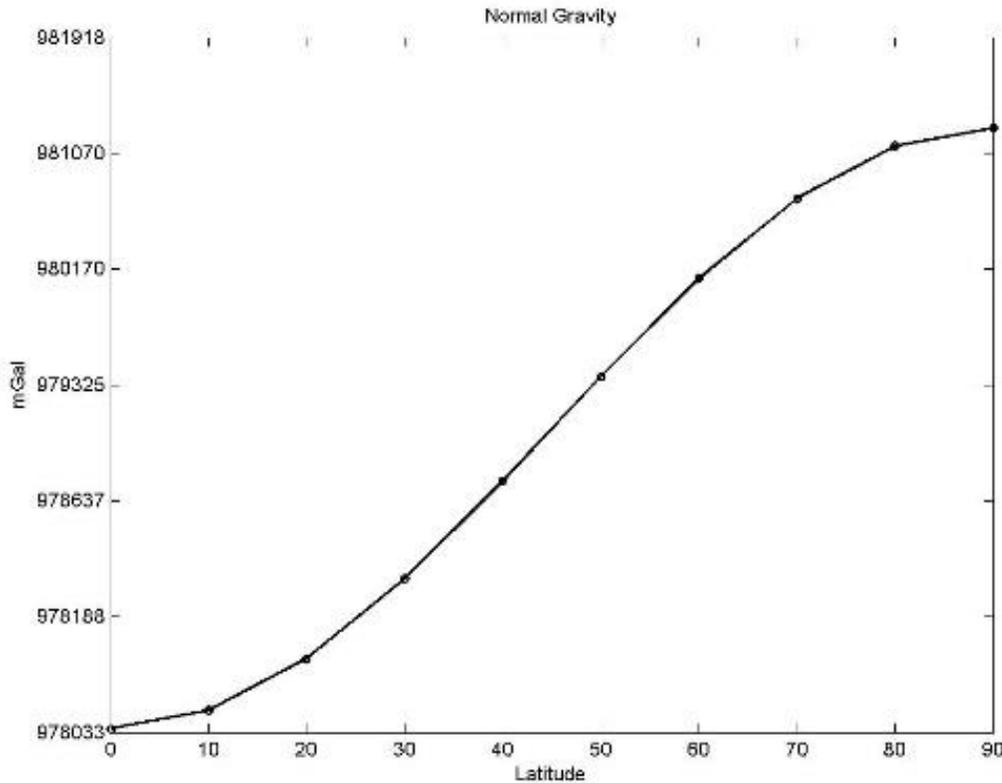


Figure 2.8.1. Change in normal gravity from equator to north pole

It is also possible to estimate how much error you introduce into your data if the horizontal location is not accurate. This only applies to the north-south direction since normal gravity only changes with latitude and has no effect for east-west changes. For a radius of 6378137 m of the earth, an estimate of the length of one arc second is about 30m meters on the surface of the earth. Thus, for an error of one meter in north-south positioning, the latitude error is less than 1  $\mu$ Gals at latitude 45N, and even smaller when it approaches to either the poles or the equator. With the advent of GPS this accuracy can be easily achieved for horizontal positioning (centimeter level can usually be obtained with carrier phase differential GPS).

### 3. Geodetic and Body Frame Transformations

#### 3.1 Calculation of Navigation Frame Velocities from Geodetic Positions

The position read from the GPS receiver are stored in geodetic Latitude and Longitude variables. This position will depend of the datum used by the GPS system. These positions need to be transformed to the transform to local tangent plane velocities for calculating Eötvös corrections.

Using WGS84 ellipsoid parameters

$e^2 = 6.694379990141089e-003$  Eccentricity squared  
 $a = 6378137$  m Equatorial radius  
 $b = 6356752.3141$  m Polar radius  
 $\phi$  = gravity meter latitude  
 $\lambda$  = gravity meter longitude  
 $f = \frac{(a-b)}{a} = 0.00335281068$  Earth flattening  
 $W = 7292114 e^{-11}$  rad/s Earth rotation rate

We can calculate East and North velocities in units of m/s by using from geodetic coordinates

$$V_N = \frac{a (1-e^2) \dot{\phi}}{(\sqrt{1-e^2} (\sin(\phi))^2)^3} \quad (3.1.1)$$

$$V_E = \frac{a \dot{\lambda} \cos(\phi)}{\sqrt{1-e^2} (\sin(\phi))^2} \quad (3.1.2)$$

And the corresponding north and east acceleration can be calculated as

$$a_N = \dot{V}_N \quad \frac{m}{s^2}$$

$$a_E = \dot{V}_E \quad \frac{m}{s^2}$$

The North heading can be calculated as

$$\varphi = \text{arctg} \left[ \frac{V_E}{V_N} \right] \quad (3.1.3)$$

### 3.2 Navigation Frame to Body Frame Long and Cross Axis

We can use the rotation matrix to project the North and East accelerations in the long and cross body frame axes

$$R_N^B = \begin{bmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{bmatrix} \quad (3.2.1)$$

Then

$$a_x = a_E \cos \varphi - a_N \sin \varphi \quad \text{cross acc in } \frac{m}{s^2} \quad (3.2.2)$$

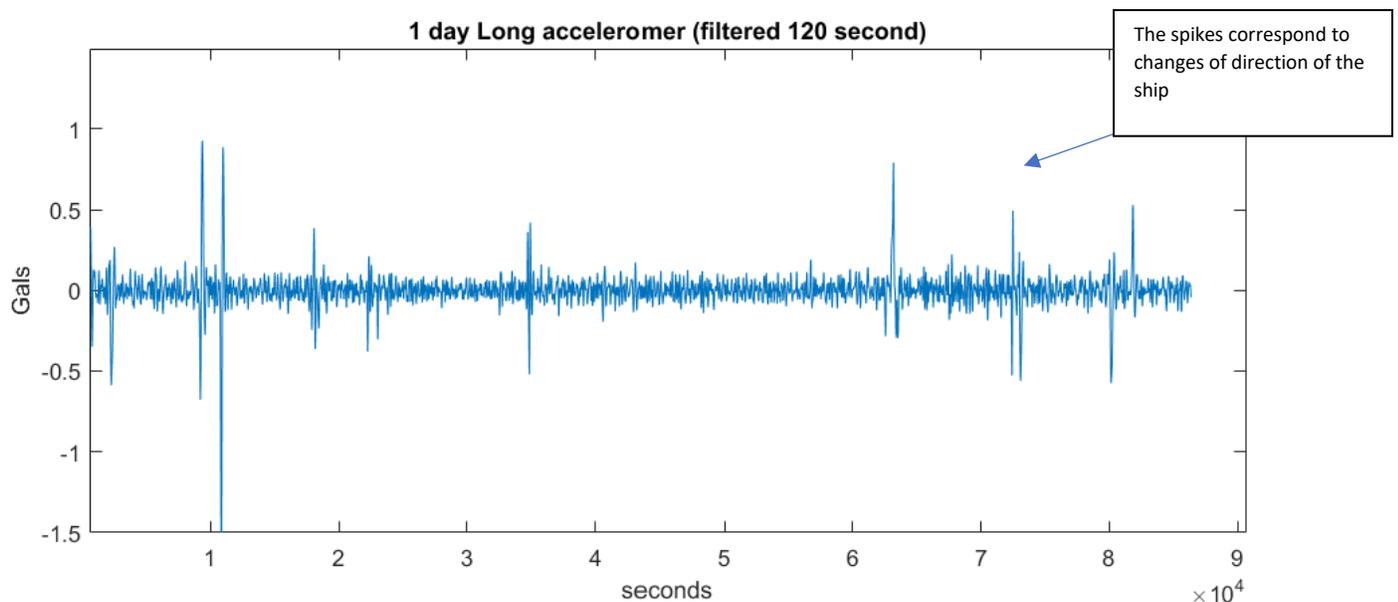
$$a_y = a_E \sin \varphi + a_N \cos \varphi \quad \text{long acc in } \frac{m}{s^2} \quad (3.2.3)$$

## 4. Other Factors Affecting Noise Levels in the Processed Data

### 4.1 Gimbal System Performance

The bearings on the gimbal system have to be in perfect conditions. These can be damaged during transport and installation of the gravity meter. It is possible to check health of the gimbal system by observing the low pass filter version of the accelerometer output for each channel. If the platform is working properly and the ship is traveling a constant speed and not changing headings, the accelerometer trace should be oscillating around zero and be between +/- 0.5 Gals band.

Figure 4.1.1. below shows a properly working gimbal.



*Fig 4.1.1. Full day of properly working gimbal system*

### 4.2 Ship Constant Heading and Speed

When the ship is changing speed or during short radius turns, the platform will get out of level. If the changes of speed are small and fast, they will have least effect on the platform verticality. Also, if the vessel turns with a big radius, it will have less effect.

In any case the small out of level effects can be compensated with the tilt compensation.

### 4.3 Noisy GPS or GPS Data with Gaps

There are a few ways in which problems with the GPS can generate noisier data. If gaps in the GPS data exist it would generate big spikes in the Eötvös correction, and platform tilt compensation therefor in the Free air gravity.

Also, if the GPS antenna is installed in a very high place in the Ship and no level arm is use in the position solution, it can induce big noises on Eötvös correction and platform, due to se swing of the GPS antenna. That can get worse when the ship is stop or going a very small speed.

### 4.4 Too Many NMEA Strings Connected to the Sensor GPS Input

When the GPS in connection is used to store GPS position in the data file, if the serial data contains many NMEA strings, all this activity can generate the main processor to loss the GPS lock and also affect the gravity logging and generate undesired spikes in the data. The sensor expects only the RMC NMEA string.

For Gravity logger versions equal or older that version 1.0.3.2 the GPS input can be read by one of the front panel USB available.

## 5. AT1M Basic Sensor Theory and Operation

### 5.1 Sensor Operation

The AT1M sensor is based on a mass fixed to a beam and balanced with an ultra-stable metal spring (zero length spring). The spring length is preadjusted to measure about near zero mGals in DGS facilities. The beam is nulled in a constant position with a feedback system based in a capacitive sensor and a magnetic coil actuator

The main output from the sensor is the current needed to keep the beam on the zero position. This current is proportional to gravity and converted with a 24 bit Analogue to Digital (AtoD) converter.

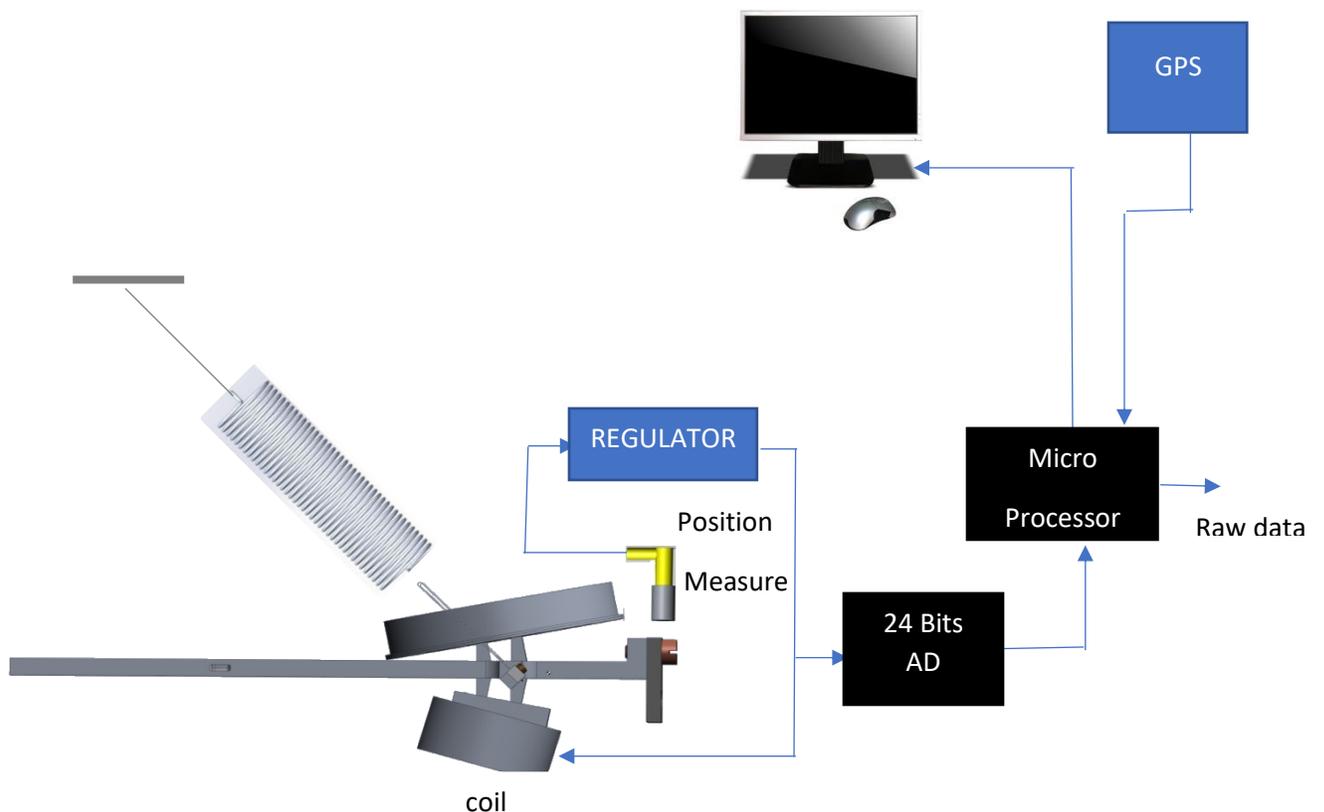


Figure 5.1.1. Sensor Basic Principle

## 5.2 Gyro Stabilized Platform Operation

The AT1M marine gravity meter uses a 2-axis gyroscopically stabilized platform to maintain the sensitive axis of the instrument aligned with the local gravity vector. The platform control uses internal damping, only the accelerometers are used by the control system to keep the platform aligned with gravity.

The accelerometers sense both gravity and motion, the accelerometer signal is feedback by the platform controller in such a way that the platform acts as a low pass filter for the output of the accelerometers.

For every axis the platform can be represented by the differential equation:

$$\ddot{\alpha} + 2f\omega_0(\alpha + \frac{\ddot{x}}{g}) + \omega_0^2(\alpha + \frac{\dot{x}}{g}) = 0 \quad (5.2.1)$$

Where:  $\omega_0$  = Platform frequency (rad/sec)

$f$  = Platform damping

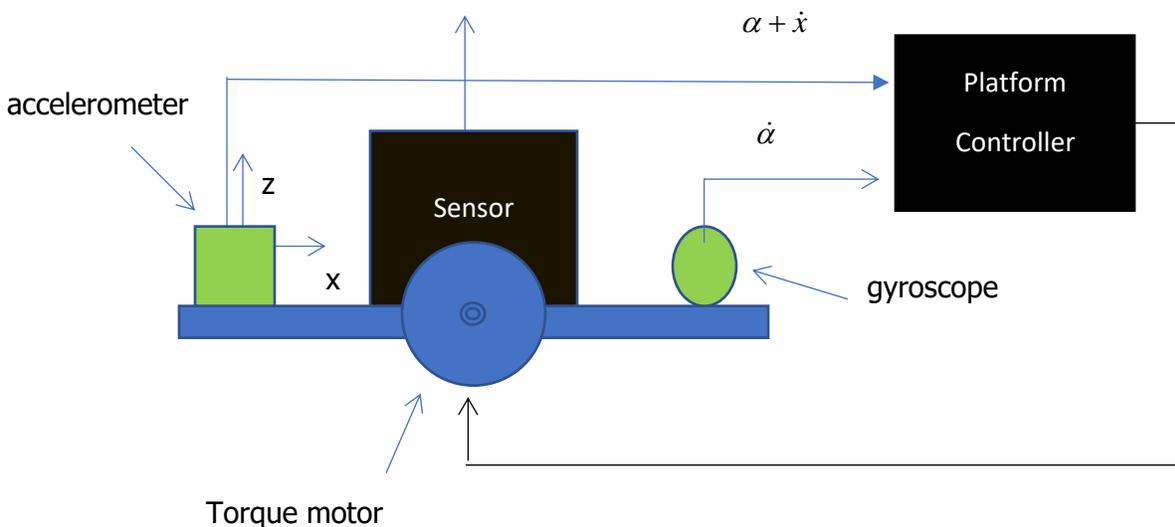


Figure 5.2.1. Platform Control Diagram

The platform relies in the fact that the ship motions measured by the accelerometer are a relatively higher frequency, when the vessel is moving a constant speed, and with constant heading, while the local vertical changes very low frequency.

Equation 2.2.1 describes a low pass filter to the accelerometer input signals. In equilibrium, the angle of error with the vertical  $\alpha \rightarrow 0$  and the effect of high frequency motions will be attenuated.

The AT1M platform uses:

Standard period  $T=240$  sec  $\omega_0 = 0.0262$  rad/s  $f = 0.707$

Long period  $T=480$  sec  $\omega_0 = 0.0131$  rad/s  $f = 70$

## 6. References

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