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# DUAL AXIS TILTMETER WITH NANORAD RESOLUTION BASED ON COMMERCIAL FORCE COMPENSATION WEIGH CELLS

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## ABSTRACT

High precision measurements and monitoring of tilt or inclination are not only essential in the field of geophysics and geodesy but also in ultraprecise force and mass measurements.
We present a new concept for high resolving tilt/ inclination measurements. Thereto a commercial electromagnetic force compensation (EMFC) weigh cell is mounted in a hanging position and loaded with a defined weight. Thus the system conforms to a pendulum. By measuring the tilt depended deflection of the pendulum with the position sensor of the weigh cell we achieved a measuring rage of ± 2 mrad. By operating the pendulum like a hanging balance and compensating the pendulum deflection with the balance internal voice coil a tilt dependent lateral force is measured. In this case the measurement range of the Tiltmeter was extended to ± 9 mrad. In both measurement modes a standard deviation of < 10 nrad (1.5 nrad filtered) within a period of 30 minutes was achieved.

***Index Terms -*** tiltmeter, inclinometer, electromagnetic force compensation

## 1. INTRODUCTION

A tiltmeter measures the inclination between the acceleration of gravity and the normal to the earth's surface. High precision measurements of tilting/ inclination are required in diverse fields. Above all, they are long-established in geophysics and geodesy where observations of local tilting are carried out and used for earthquake prediction for example [1, 2]. Local tilting bases on several natural phenomena such as wind-blown vegetation, precipitation, body waves or surface waves (seismic waves), atmospheric pressure changes deforming the ground or thermoelastic deformations and pore pressure changes as well as joint deformation related to groundwater motion [1, 2]. Besides these, earth tides are the best known effect. Depending on the location and direction of measurement, they cause tilting of the Earth´s crust in the 100 nrad amplitude range with a semidiurnal (~12.5 h) and a diurnal periods (~24 h) [2-4]. Deformations of the founding or the floor of buildings caused by moving persons or machinery were observed to be in the µrad range and are additional sources of tilting of a laboratory or a measurement setup.
In the field of force and mass metrology even small changes of the inclination of measurement setups could generate significant measurement deviations. Depending on the mechanical design of the balance lateral components of the weight force resulting from the

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tilting can be sources for measurement deviations. For instance, the torsion balance described in [5] is almost as sensitive for tilting as for force measurements.
The contribution of tilting to the measurement uncertainty can be reduced if this is monitored and its influence corrected or compensated. In current researches traceable force measurements in the piconewton range are described [6-9]. Nesterov for instance measured the force of 47 pN that is induced by the light pressure of a 7 mW laser beam acting on a mirror [8]. A tilting of the used "Nanonewton Force Facility" of just 1 nrad would generate a measurement deviation of 40 pN. Thus, a measurement of tilting with a resolution of < 1 nrad is included in the "Nanonewton Force Facility" to compensate and correct the influence of tilting.
In the field of contactless flow measurement techniques, the setup described by Diethold et al. [10] is used to determine Lorentz forces in the µN-Range. Here a 10 nrad tilt of the setup causes a measurement deviation of 0.1 µN.
In conclusion, it is obvious that local tilt measurements in the nanoradian range are not only needed in the scope of geophysics but also in various fields of metrology such as force and mass measurements.
The aim of the presented investigation is to develop a tiltmeter/ inclinometer with a reasonable resolution of ~ 1 nrad at a, compared to the state of the art, expanded measurement range of up to ~ 17 mrad (1°). This would extend the field of application of such highly resolving tiltmeters. Only one device would be needed to cover both: measurements of very small and large changes of inclination with a resolution of ~ 1 nrad. Furthermore, calibrations of tiltmeters with different measurement ranges could be carried out with one setup.

## 2. STATE OF THE ART

Several principles for the measurement of tilt/ inclination are known. The most common ones apply pendulums, gas bubbles (level) or liquid surfaces as a reference [1].
Borehole tiltmeters established in the field of geophysics offer a resolution of 1-5 nrad at a measurement range of 50 - 200 µrad [1, 2, 11]. The Askania borehole tiltmeter was developed in the late 1960s and was later manufactured by BODENSEEWERKE GEOSYTEM GmbH. It still represents the state of the art in the field of geophysics. Basically it consists of a 0.6 m pendulum, a capacitive deflection measurement and a force feedback applied by Helmhotz coils [1]. Unfortunately it is not produced anymore.
The Leica Nivel 210 inclinometer made by LEICA GEOSYSTEMS AG features a resolution of 1 µrad and a measurement range of ±3 mrad [12]. It uses a liquid horizon which is optoelectronically sensed.
The tilt measurement included in "Nanonewton Force Facility" works on a similar principle as the Askania borehole tiltmeter [6, 7, 8]. The inclination dependent deflection of a pendulum is measured with an interferometer and is compensated by an applied feedback force that is generated electrostatically. The applied capacitor voltage is then a measure for the force and thus for the inclination. The resolution is given with < 1 nrad.
In Summary it can be stated, that a resolution of ~ 1 nrad represents the state of the art in the field of tilt or inclination measurements. However, the measurement range of those high resolution devices is very limited.

## 3. MEASUREMENT SETUP

As well as the state of the art devices, our chosen principle of measurement bases on a pendulum. The pendulum is realized by the mechanics of a commercial electromagnetic force compensation (EMFC) weigh cell made by SARTORIUS WEIGHING TECHNOLOGY GmbH. The weigh cells base on standard parts [13] but were optimized for our purposes. In contrast to their designated use, the weigh cells are not mounted horizontally but in a vertical (hanging) position as shown in Fig.1. and Fig 2. The hanging weigh cell consists of a pendulum which is designed as a monolithic parallel spring guidance made of aluminum, a weight *m* attached to this pendulum as well as a transmission lever system, an optical position sensor and a voice coil. The position sensor is realized by a fixed LED and a fixed differential photo diode. An aperture mounted to the transmission lever is placed between the two diodes. Thus, the illumination of the two sensitive areas of the photo diode changes when the lever moves [14].The Tiltmeter comprises of two orthogonal axes, see Fig. 2. The measurements can be carried out in two different modes.

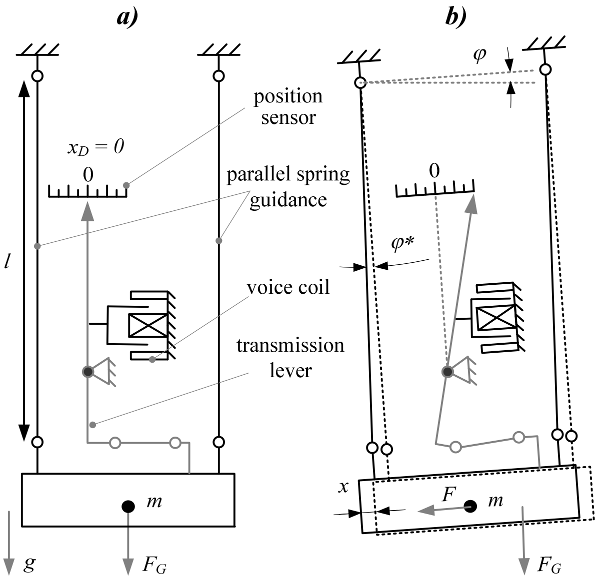


*Figure 1: a) hanging weigh cell b) weigh cell tilted by φ; in this case the coil is not generating a compensation force*

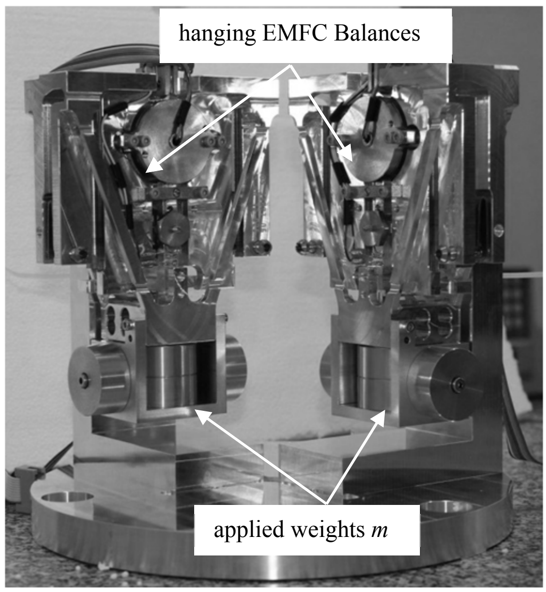


*Figure 2: dual axial Tiltmeter realized by mounting two EMFC balances in a hanging position*

### 3.1 Pendulum Mode

In the Pendulum Mode the tilt related pendulum deflection is measured with the position sensor of the EMFC balance.

A tilting of the setup by the angle $\varphi$ generates the lateral force component $F$, see Fig. 1. Depending on the length $l$ of the pendulum and the stiffness $c$ of the weigh cell the force component $F$ deflects the weight $m$ by the distance $x$ whereas $g$ is the gravitational acceleration ($F_G = m \cdot g$):

$$\varphi = x\left(\frac{c}{m \cdot g} + \frac{1}{l}\right) \tag{1}$$

The maximum deflection arises if the stiffness *c* of the weigh cell approaches zero or the mass *m* is chosen to be infinite. In this case the angle deflection of the pendulum $\varphi^*$ is equal to the tilting of the system $\varphi$. The voice coil can be short-circuited and thus acts as a damper of the μοϖεμεντ of the penδulum. The stiffness of the system is in the range of $c \approx 200$ N/m [15]. Assuming a reasonable resolution of the deflection $x$ of < 0.2 nm, a length of the pendulum $l = 75$ mm and a mass of $m = 0.57$ kg, a useful resolution of the tilt $\varphi$ of < 10 nrad will be achievable. With the maximum deflection of $x \approx \pm 40$ µm a measurement range of $\varphi \approx \pm 2$ mrad can be attained.
Measurements in this Pendulum Mode have been carried out by amplifying the Signals of the Position sensor with a self-made electronics and recording it with Agilent 34411 Multimeters.

### 3.2 Balance Mode

In the Balance Mode the tilt proportional lateral force $F$ of the weight force $F_G = m \cdot g$ acts on the balance and is measured. In this case the system is used as a hanging balance and the pendulum deflection $x$ or $\varphi^*$ is controlled to zero by generating a counterforce with the voice coils. The electric current applied in the voice coil to produce the counterforce is then proportional to the tilt. The force $F$ to compensate can be expressed as:

$$F = F_G \cdot \sin\varphi = m \cdot g \sin\varphi \tag{2}$$

With the resolution $\Delta m_{Balance}$ of the applied compensation balance the resolution of the tilt measurement can be estimated with:

$$\Delta\varphi = \frac{\Delta m_{Balance}}{m} \tag{3}$$

Thus, if the mass is chosen to be $m = 0.57$ kg a balance with a resolution of 1 µg is needed to resolve a tilt angle of $\varphi = 1.76$ nrad. Assuming a measurement range ± 5 g, the range of the tilt measurement can be increased by the factor of 5 to ± 9 mrad. The resolution can be increased by applying a bigger mass but with a loss of measurement range, as predicted by equation (3). Anyway, the limitation of equation (1) must be considered in the balance mode as well. The minimum resolvable tilt is limited by the resolution of the deflection x and the length of the pendulum even if the tilt proportional lateral force is bigger than the resolution of the balance. This is a difference to the application of the balance in a horizontal orientation.
Measurements in this Balance Mode have been carried by the recording the balance values with the corresponding electronics of the SARTORIUS Weigh Cells.

## 4. MEASUREMENT RESULTS

### 4.1 Calibration of the Sensitivity

The mass of the applied weights was chosen to be ~780 g. Additionally to this known mass the mass of the movable parts of the weigh cell must be considered. All parts above the fixed joint (see Fig. 1) act as a counterweight. Therefore the effective mass *m* is not known and the system must be calibrated to find its sensitivity.
For the calibration of the Tiltmeters a high resolving Tilttable was developed [16]. It offers a range of ± 18 mrad (1°), a design resolution of 35 nrad and can carry a load of ~150 kg. The measured uniaxial repeatability of the tilt table was proved to be better than 0.5 µrad. The Tilttable was calibrated using a MÖLLER WEDEL ELCOMAT 3000. The interpolation

deviation from the fitted 3rd degree polynomial is less then ± 2 µrad in the whole range of both axes [16]. This contribution must be considered for the uncertainty of the calibrated characteristical curves of the Tiltmeters.
To calibrate the Tiltmeter it was placed on the Tilttable whereby the axis of the table and the Tiltmeter where aligned precisely. The angles where set stepwise holding each step for two minutes. Meanwhile the Tiltmeters signals where stored to the computer.

### *4.1.1 Pendulum Mode*

The measured relation between the angles set by the Tilttable and the voltage of the Position Sensor is shown in the upper section of *Fig. 3 a)* and *b)* (blue dots). The S-shaped curve can be explained with the characteristic of the double photodiode Position Sensor. The characteristical curves have been fitted with 5th degree polynomials (red lines). The linear contribution of the sensitivity can be given as $Sx_{Pendulum}$= 2.09 · $10^{-4}$ rad/Volt and $Sy_{Pendulum}$= -2.52 · $10^{-4}$ rad/Volt. Based on the measurements and the computed polynomials the fit residuals (interpolation deviation) shown in the lower section of *Fig. 3 a)* and *b)* have been calculated. The given uncertainty corresponds to the interpolation deviation of the Tilttable of 2 µrad. Consequently the interpolation deviation of the Tiltmeters x-axis can be given as < ± 10 µrad and < ± 5 µrad for the y-axis respectively. The measurement range is ± 2 mrad for both.

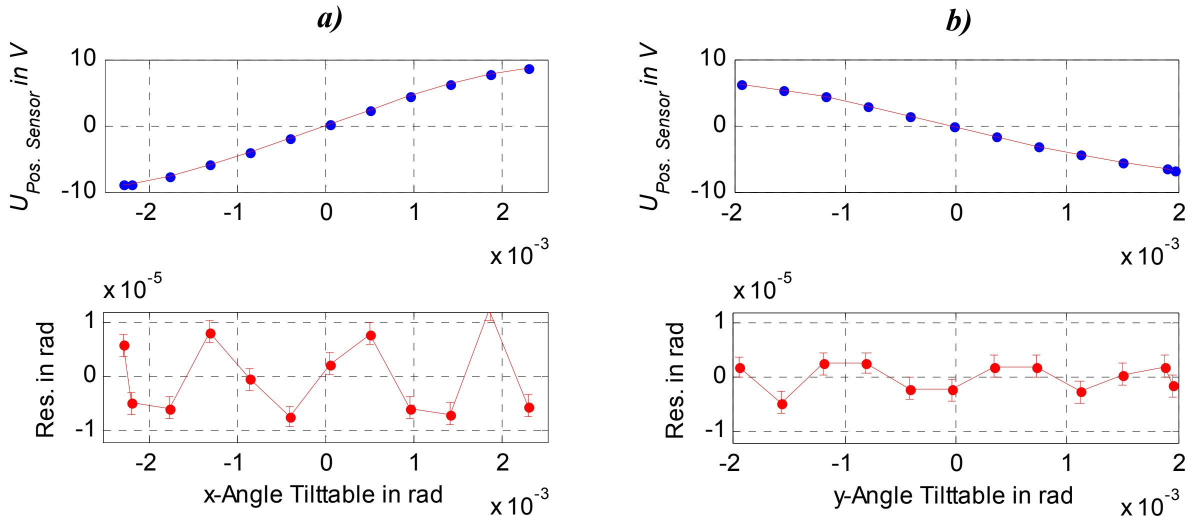


*Figure 3: measured characteristical curve of the tiltmeters axis using the Pendulum Mode and the fit residuals for a): x-axis and b): y-axis*

### *4.1.2 Balance Mode*

The corresponding measurements of the characteristical curves when the Tiltmeter is used in the Balance Mode are shown in *Fig. 4*. A good linear behaviour can be observed. Consequently the characteristical curves have been approximated with a linear function resulting in an angle sensitivity of $Sx_{Balance} = Sy_{Balance} = 1.76 \cdot 10^{-3}$ rad/g for both axes. With the weigh cell resolution of 1 µg one digit of the balance electronics corresponds to 1.76 nrad. Due to the measurement range of ± 5 g the measurement range of the Tiltmeters used in the Balance Mode can be given with ± 8.8 mrad. Based on equation (3) the effective mass of the applied weights can be estimated to be ~570 g. The interpolation deviation is shown in the lower section of *Fig. 4 a)* and *b)*. Due to the linear fit it represents the linearity deviation of the system. This linearity deviation can be proven to be less than ± 3 µrad in the whole range and is within the Interpolation deviation of the Tilttable. The deviation of 3 µrad conforms to $\Delta m$ ~ 1.5 mg of the balance display. Based on the datasheet values of the weigh cell [13] an even better linearity is expected but due to the limitations of the Tilttables uncertainty it could not be proven in this experiment.

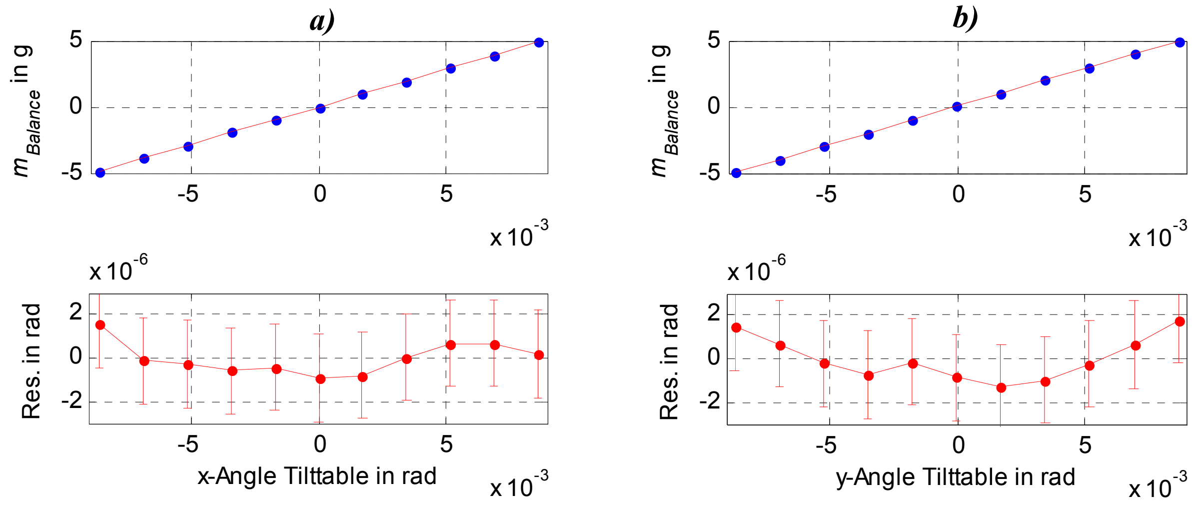


*Figure 4: measured characteristical curve of the tiltmeters axis using the Pendulum Mode and the fit residuals for a): x-axis and b): y-axis*

Comparing the two modes of measurement concerning measurement range and interpolation deviation (Nonlinearity) shows clear advantages of the Balance Mode. With the applied weights of $m$ ~ 780 g its measurement range is fourfold bigger than in the Pendulum Mode. By lowering the mass of the weights the measurement range of the Balance Mode could easily be extended. Furthermore even in this bigger range the interpolation deviation is at least 3 times smaller than in the Pendulum Mode.

## 4.2 Cross sensitivity

The cross-sensitivity of a Tiltmeter represents the signal of the axis not being moved while the other axis is tilted. It can arise from two reasons or their combination, see Fig. 5.

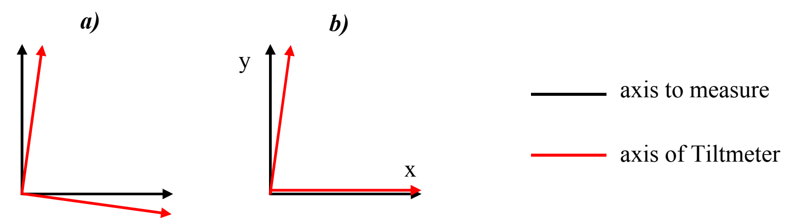


*Figure 5: reasons for cross sensitivity of a tilt measurement a): axes to measure are imperfectly aligned to the axis of the Tiltmeter and b): axes of the Tiltmeter are not perpendicular aligned*

If the Tiltmeter axes are perfectly perpendicular but not coincident with the tilted axes (case *a)* in Fig. 5) both Tiltmeter axes will display the same cross error while a measurement. In this case the resulting cross error can be eliminated analytically. If the Tiltmeter axes are not perpendicular but one of its axes is perfectly coincident with the tilted axis (x-axis in case *b)* in Fig. 5) the y-axis will display a cross error when the x-axis is tilted. In contrast the x-axis will not show a cross error when the y-axis is tilted. This is a device inherent error and must be calibrated to eliminate it in the later measurements.

For this experiment the Tilttable was used. The relative cross error of the Tilttable is within the limits of $\pm 1.2 \cdot 10^{-4}$ ($k = 2$) in it whole range [16].

Prior to the calibration the axes of the Tiltmeter where aligned with respect to the axes of the Tilttable resulting in an adjustment similar to case *b)* of Fig. 5. This was done by tilting the y-axis of the Tilttable and rotating the Tiltmeter around its z-axis in a way that the x-axis shows a minimum signal. The limits of this adjustment arise from stick-slip between the table and the Tiltmeter. Based on this adjustment the signal of the x-axis when the y-axis is tilted was reduced to $\sim \pm 1\mu$rad, see Fig. 6 *a),* blue curve. This cross error represents the error due to misalignment of the Table and the Tiltmeter axes (Fig. 5 *a)*). Afterwards the x-axis was tilted and the y-axis was measured (Fig. 6 *a),* green curve). This error comprises the misalignment of the Table and the Tiltmeter axes as well as the Tiltmeters inherent cross error due to nonperfect perpendicularity of its axes. Thus it represents the sum of case *a)* and *b)* from Fig. 5. Subtracting the error due to misalignment of table and Tiltmeter results in the inherent cross error of the Tiltmeter (red curve of Fig. 6 *a)*).

The same investigation was done in the Pendulum Mode afterwards. Both absolute cross errors are shown in Fig. 6 *b)*. A parabolic shape can be observed for both Modes. Fitting the cross error using a quadratic function without linear and absolute contribution results in the cross sensitivity of the Tiltmeters of $Sc_{Pendulum} = -0.37$ rad/rad² and $Sc_{Balance} = -0.031$ rad/rad².

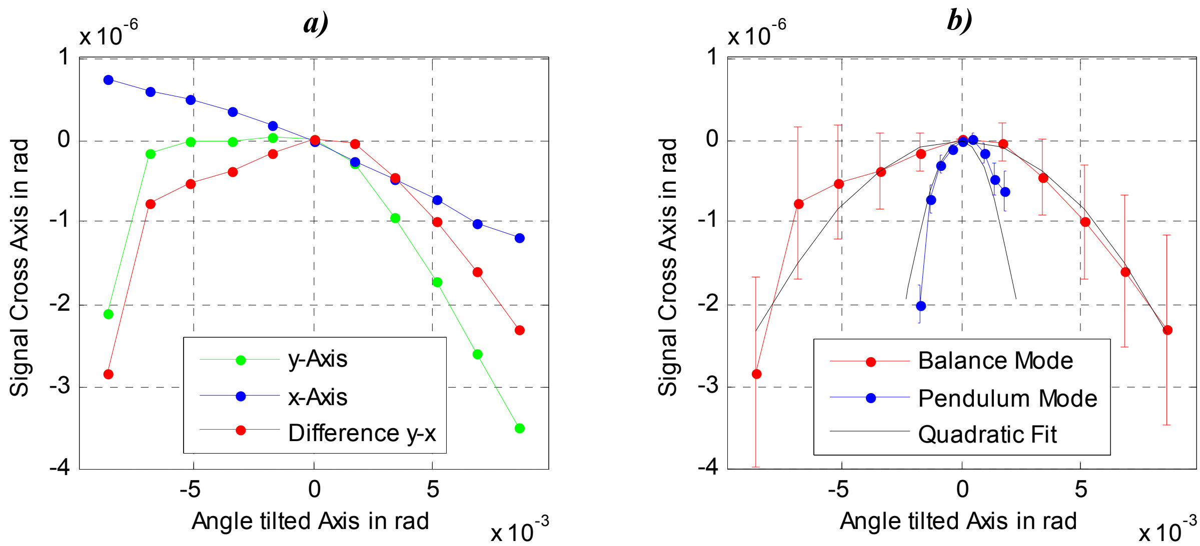


*Figure 6: a): single cross error of the two Tiltmeter axes used in the Balance Mode and the resulting cross error represented by the difference of the two axes, b): resulting cross error of Pendulum and Balance Mode including the uncertainty of the Tilttable*

Both Modes base on the identical pendulum but the measured cross error differs. This can be explained as follows: Due to the parallel spring guidance used as pendulum the cross axis is in a labile equilibrium when the Tiltmeter is tilted around the main axis. If now the axes are not perfectly perpendicular the cross axis deflects out of this labile equilibrium. Once this happens the sensitivity rises the more the main axis is tilted. This results in a quadratic behaviour of the cross sensitivity. In contrast to this the pendulum deflection is compensated in the Balance Mode. This might be the reason for the tenfold better performance of the Balance Mode.

### 4.3 Noise and reasonable Resolution

To specify the reasonable resolution of the noise the Tiltmeter was placed on a granite stone in the base floor of our laboratory building. The granite stone is placed on two granite blocks with four machine feet between. The noise should be examined within a period of 30 minutes. In longer measurements periodical tilts that were observed in the lab would affect the specified noise.

Figure 7 *a)* shows the Signals of the two axes measured in the Pendulum Mode with a sampling rate of 2.2 Hz. The standard deviation within the 30 minutes were determined to $\sigma_x = 8.9$ nrad and $\sigma_y = 45.6$ nrad respectively. A cross change of the electronics, the multimeters and the cables did not lead to an improvement of the y-axis signal. Finally the Tiltmeter was rotated by 90 ° with respect to the axes of the granite stone resulting in a cross change of the standard deviation. Hence a crucial contribution to the standard deviation seems to be vibrations of the stone and the lab.

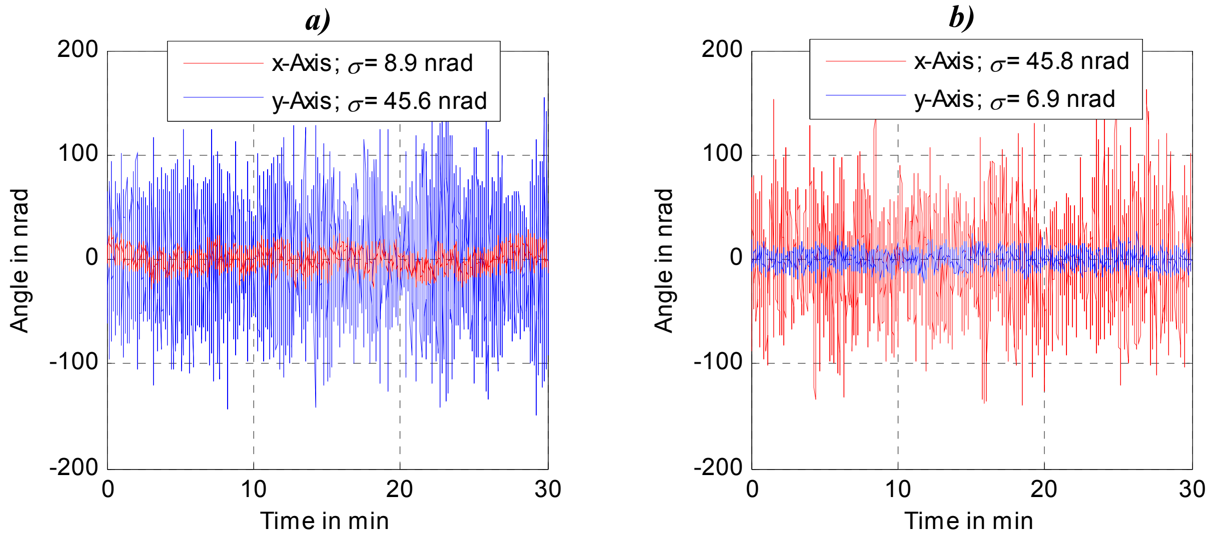


*Figure 7: a): signals of the two axes measured in Pendulum Mode (2.2 Hz), b) Signals after the Tiltmeter was rotated by 90° around its z-axis*

When the Tiltmeter is operated in the Balance Mode the dependence on the measurement direction was not observed, see. Fig 8 *a)*. It is assumed that the controller, that controls the force compensation, damps the critical vibrations. The standard deviation was determined to $\sigma_x = 7$ nrad and $\sigma_y = 7.3$ nrad at a sampling frequency of 10 Hz.

In Figure 8 *b)* the dependence of the standard deviation on the integration time of the signal is computed. For the Pendulum Mode an optimal integration time of ~120 s can be found resulting in a standard deviation of 1.1 nrad of the better axis. At this integration time the standard deviation of the signals measured in Balance Mode is in the range of 1.4 – 1.9 nrad. Hence, in this case the performance of the Pendulum Mode seems to be slightly better than of the Balance Mode. The reason might be the controller parameters used to control the force compensation. A periodical control deviation at ~ 0.15 Hz was observed in all measurements

using the Balance mode. The factory settings of the controller are optimized for a use of the weigh cells in a horizontal adjustment and at smaller applied load. An optimization of these controller parameters might improve the standard deviation.
However the measurements with the Pendulum Mode (Fig. 7) showed obviously that the observed performance of the Tiltmeters in terms of noise is strongly depended on the environment and should be repeated in more quiet surroundings.

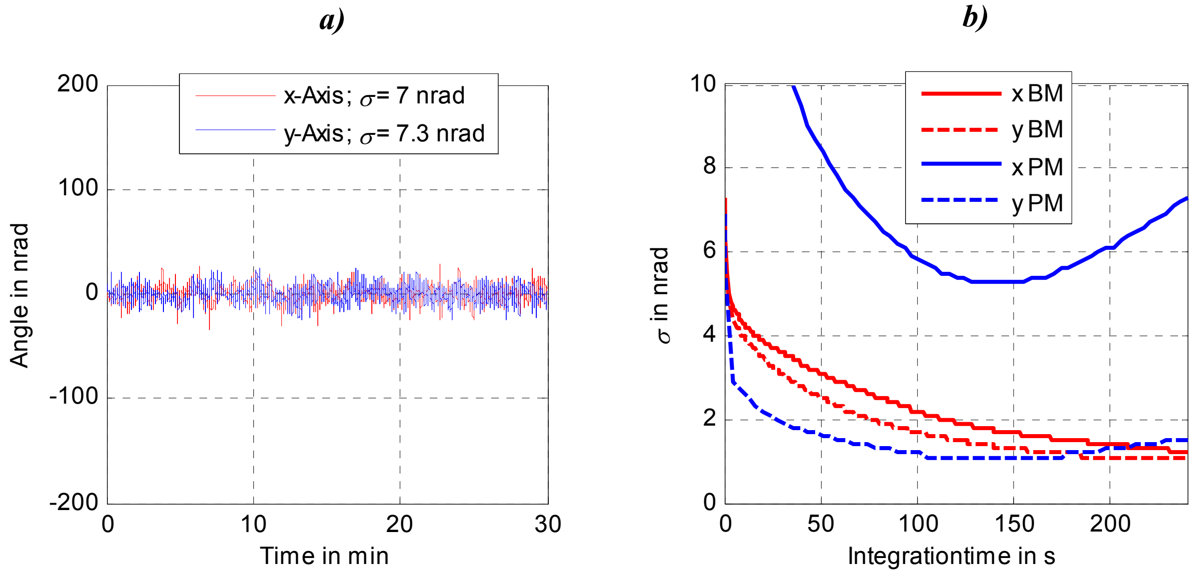


*Figure 8: a): signals of the two axes measured in Balance Mode (10 Hz), b) Standard deviation of the Signals depending on the integration time, BM: Balance Mode, PM Pendulum Mode*

### 4.4 Long Term measurements

In the next step long term measurements of the tilting have been carried out using the Pendulum Mode. The setup was aligned with respect to the horizontal axis of the granite stone which are oriented in WNW- and in SSW-direction. The measured tilt around the SSW-axis of earth is shown in Fig. 9.
The tilt around the SSW-axis mainly comprises of a long term drift and periodical contributions. The spectrum of this trend corrected signal shows the two main contributions with 50 nrad at a period of ~ 12.47 h and 30 nrad at a period of ~ 24.94 h which correspond to the influence of the earth tides. The earth tides are generated by the relative movement of earth, sun and moon cause different harmonic components depending on the direction of measurement and the latitude of the location. The main components of tilt around the north south axis for our location of the lab are listed in table 1.
The measured harmonic components are in a good agreement with the expected components or the combination of those. It must be considered that the Tiltmeter was not exactly aligned to the NS axis on which the predicted values of table 1 base.
The drift might be caused by long term drift of the stone, the lab or the building and/ or might be due to long term and temperature drifts of the Tiltmeter. As well as the noise this effect should be investigated in a more defined and quiet surrounding.

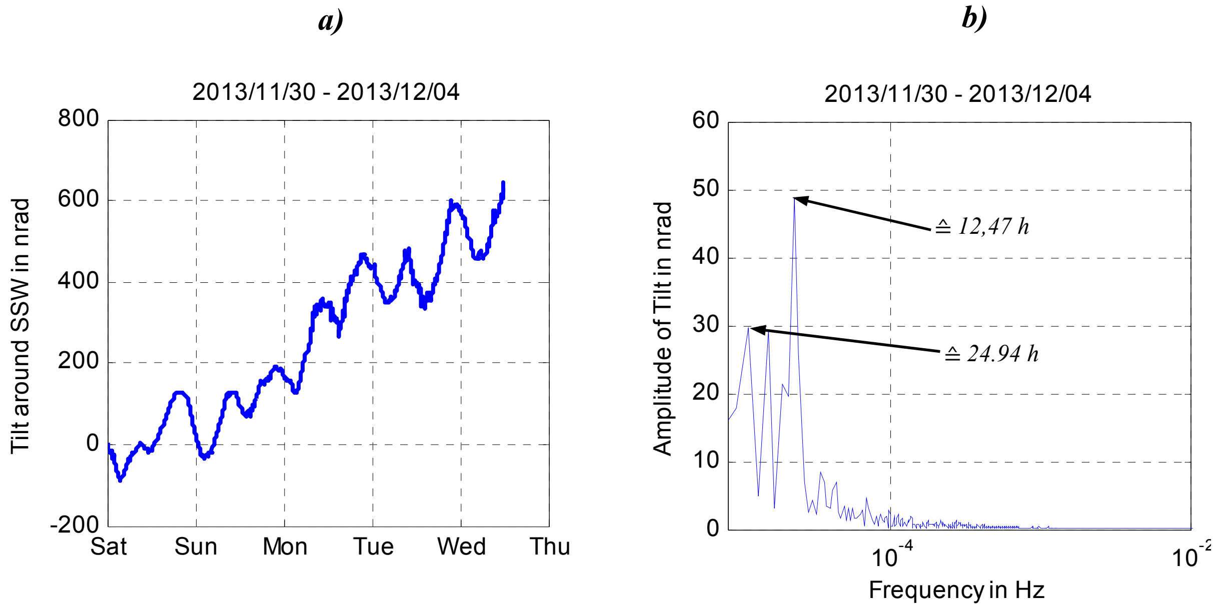


*Figure 9: a): long term measurements influenced by the earth tides and a long term drift b) spectrum of the trend corrected long term measurement*

*Table 1: estimated contributions of the earth tides to the measured tilt around north south axis of earth at the location of our lab [4]*

| Harmonic Component | Period | Amplitude |
|---|---|---|
| **M2 Moon** | 12.42 h | 44 nrad |
| **S2 Sun** | 12.00 h | 20 nrad |
| **K1 Moon/ Sun** | 23.94 h | 18 nrad |
| **O1 Moon** | 25.82 h | 13 nrad |

## 4.5 Conclusions

We have proposed a novel design for tiltmeters basing on commercial weigh cells. The tiltmeters can be operated in two different modes. The measured parameters are summed up in table 2.

*Table 2: summary of the parameters of the tiltmeters*

| | Pendulum Mode | Balance Mode |
|---|---|---|
| **Range** | $\pm 2 \cdot 10^{-3}$ rad | $\pm 9 \cdot 10^{-3}$ rad |
| **Sensitivity** | $\sim 2 \cdot 10^{-4}$ rad/Volt | $1.76 \cdot 10^{-3}$ rad/g |
| **Cross Sensitivity** | -0.37 rad/rad² | -0.031 rad/rad² |
| **Noise** | < 10 nrad (2.2Hz) | < 10 nrad (10Hz) |
| **Noise filtered Signal** | 1.1 nrad ($T_I$ = 120 s) | 1.4 nrad ($T_I$ = 120 s) |

In the Balance Mode we achieved a measurement range of ± 9 mrad and a signal noise of < 10 nrad at a sampling frequency of 10 Hz. After applying a filter (integration time of two minutes) the noise can be reduced to < 1.5 nrad. In the Pendulum Mode we achieved a similar noise but a smaller measurement range. Thus our tiltmeters reach almost the state of the art resolution of ~ 1 nrad at a remarkable extended measurement range. The measurements showed that the achieved noise is obviously dependent on the environmental parameters (vibrations) of the laboratory. We also investigated the cross sensitivity, a parameter which is often not indicated in datasheets of tiltmeters. Here we observed a quadratic cross sensitivity of 0.031 rad/rad² in the Balance mode. This corresponds to a relative error of 500 ppm in the whole measurement range of 8.8 mrad.
Furthermore long term measurements proved, that the tiltmeters are capable for the measurements of small fundamental effects such as the earth tide related tilting of the earth crust. Both, the noise of the systems as well as their long term performance will be further investigated in the stable environment of the Geodynamic Observatory Moxa.
Moreover the vacuum compatibility of the systems will be observed in the future.

## ACKNOWLEDGEMENTS

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