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First test of tiltmeters for the link system of CMS

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Abstract

In this note we present first tests done with the tiltmeters proposed as the key elements of the Laser Level systems to be used in the CMS alignment system. The reponse of the sensors under moderated longitudinal and transversal tilts is studied and intrinsic performance is extracted.

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1 Introduction

In the current alignment scheme for the CMS experiment [1] the ϕ coordinate will be monitored using Laser Level boxes [2]. The Laser Level boxes contain mainly a laser source and a tiltmeter. The tiltmeters will measure the ϕ angle with respect to the gravity and will allow to connect the measurements between the Tracker [3] and Muon Chambers Systems [2]. Tracker and muon detectors must be aligned with a precision better than 20μrad in the bending plane.

The tiltmeters investigated in the present work were manufactured by Applied Geomechanics Incorporated (AGI) [4]. We have calibrated the output response of two of these sensors against longitudinal tilts and studied the eventual degradation of the response when the sensor is operated under a small traversal angle.

This document is organised as follows. In section 2 a short technical overview of the tiltmeters is given. Section 3 is a description of the setup used. In section 4 we introduce the definition of some angles that play an important role in order to understand some future results. Section 5 introduces to the expected effects of transversal tilts while the calibration of the sensors for longitudinal tilts is presented in section 6. Measurements of the response to the transversal tilts are given in Section 7. Finally, the conclusions are drawn in section 8.

2 The working principle

Tiltmeters or tilt sensors measure tilts with respect to the most stable reference: the vertical *gravity vector*. Tiltmeters are high precision sensors. They measure angular position and rotational movement of the elements to which they are attached.

The sensor operation is based on the fundamental principle that an enclosed bubble, suspended in a liquid, will always orient itself perpendicular to the gravity vector. The bubble (see Fig. 1) is allocated in a liquid-filled case, with three electrodes. When an AC voltage is applied across the two excitation electrodes, the AC output measured at the central pick-up electrode changes as a function of the tilt angle.

The conversion of AC current to DC current is obtained by means of a Signal Conditioning Unit (SCU). An adequate SCU can be purchased together with the AGI equipment. It also allows to monitor the environmental temperature. The tiltmeter working range depends on the output gain, being ± 4 degrees (higher gain) or ± 10 degrees (lower gain).

3 Setup

A mechanism providing rotations of the order of the microradian is necessary to cope with the accuracy of the tiltmeters in test. We used a 450 mm long arm tripod which can be moved (by one of its ends) in steps of 0.5 μm (that is $\approx 1\mu$rad). The tripod sustains on three knobs that can be moved independently. A sketch of this structure can be seen in Fig. 2.

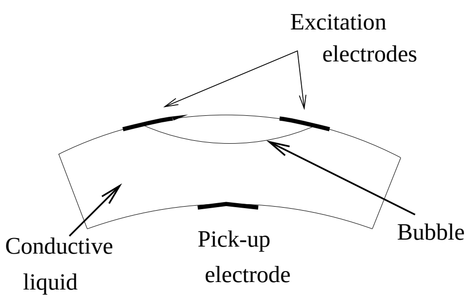

Figure 1: Schematic structure of a tiltmeter.

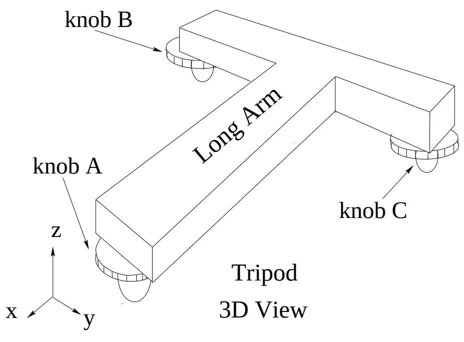

Figure 2: 3D view of the tripod used in the tests.

The sensors will be located on top of the longest arm. When studying longitudinal tilts, the sensor is placed along the longest arm. For transversal tilts the sensor is placed orthogonal to the longest arm. In that way, the knob called 'A', will be the only one manipulated. The sensors (see Fig. 3) are screwed on a platform, which is the interface between the tripod and the sensors. The knob ‘A’ tilts the tripod along the Z axis (axis definition is in Fig. 2). The Z displacement is measured by a length gauge HEIDENHAIN with a resolution of 0.5 μm.

The tripod, platform and sensors were placed on a stable bench in the basement of a building in order to minimise any disturbing motion. To avoid any scratch of the bench, the knob sits on commercial KENNAMETAL ‘pills’. These basis are smooth at the μm scale, but the bottom and upper sides are not necessarily parallel. The temperature of the laboratory was kept around 20$\pm$2 degrees Celsius (air conditioned room). Fig. 3 shows the whole arrangement.

4 Definition of the tilts

Tiltmeters are 1D sensors. This means that they are intended to measure tilts along one direction. In a frame local to the sensor (see Fig. 4a)) one measures tilts along the X direction. The calibration of a tiltmeter consists in finding a relationship between the angle moved in the ZX plane (see Fig. 4b)) and the voltage measured by its electronics.

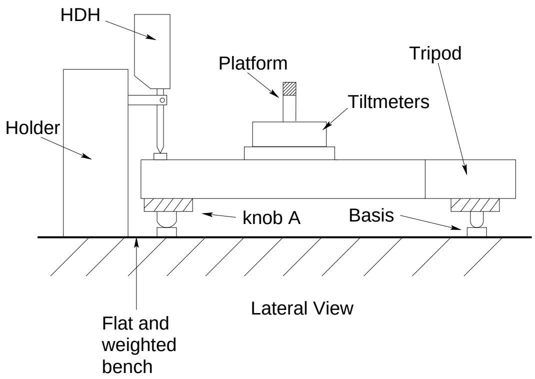

Figure 3: Lateral view of the bench, tripod, tiltmeters and Heidenhain setup. The Heidenhain is supported by a heavy holder, to ensure it does not move when the tripod tilts.

To study the effect of a transversal tilt we have to measure how the former angle vs voltage relationship changes when the operating conditions force the tiltmeter to measure the longitudinal angle under a tilt contained in the ZY plane. This effect is exaggerated in Fig. 5. If the change were not negligible, then the transversal tilt would have to be monitored and used to correct the measured angle.

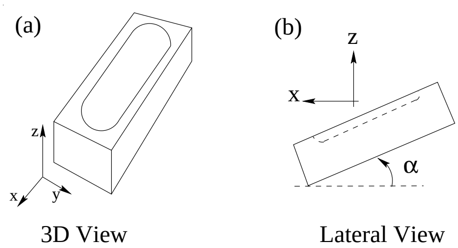

Figure 4: In a tiltmeter: a) Axis definition for the tiltmeter. b) Lateral view for a pure longitudinal tilt.

From now on, we will call *longitudinal* (α in Fig. 4b)) the tilt contained in the ZX plane (longitudinal angle for the tiltmeter) and *transversal* (χ in Fig. 5) the tilt contained in the ZY plane (transversal angle for the tiltmeter).

In practice it is almost impossible to achieve in the laboratory such independent longitudinal and transversal tilts at the μrad level. Any tilt (longitudinal or transversal) will have a *pollution* of the corresponding orthogonal component. To cope with this uncertainty we will introduce a degree of freedom in the calibration, represented by a new angle ϵ referred as the *misalignment* . This angle will carry the information about the quality of the tilt. The misalignment may be present in two ways:

- The X axis of the tiltmeter and the ideal tilt axis coincide, but the real tripod tilting angle deviates from the ideal (Fig. 6a)).
- The tripod provides a perfect tilt in its XZ plane but the longitudinal axis of the tiltmeter does not coincide

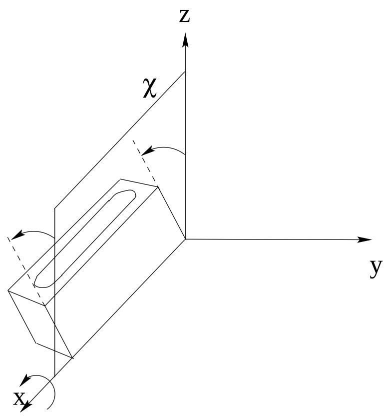

Figure 5: Tiltmeter affected by a transversal tilt.

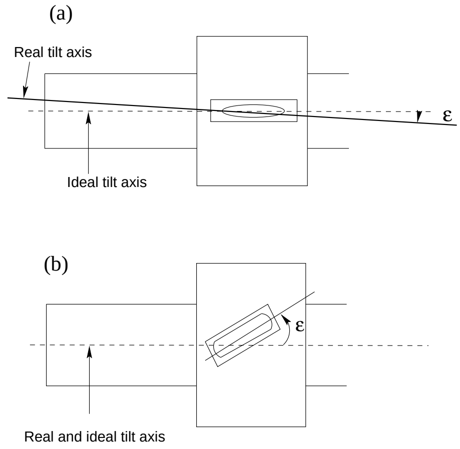

Figure 6: Misalignment angle ϵ in a longitudinal tilt. Top view.

with it (Fig. 6b)).

Both cases have been differentiated but, in fact, they describe the same phenomena. Therefore any mispositioning ϵ between the tripod and the tiltmeter local frames translates in a bad quality of the tilt (bad quality here means that the rotation has two components).

Besides this, another angle γ will be introduced to take into account that tiltmeters might be consciously lifted to get a higher response, for instance to take the sensors out of the zero (perpendicular to gravity) state. What happens is that the zero voltage state is, due to the internal arrangement bubble-electrodes, a stable point: the response is always zero under transversal tilts.

All angular definitions can be seen in Fig. 7. Here the tiltmeter is represented by a unitary vector $\overrightarrow{v}$ (contained in the plane X'Y') that subtends an angle ϵ with the -Y axis. The plane represents the surface where the sensors are positioned. For a *pure* longitudinal calibration, ϵ should be equal to $\frac{\pi}{2}$, and 0 for a *pure* transversal operation. α is the angle measured by the tiltmeters and θ is the angle moved by the long arm of the tripod. Angles θ and α coincide, in a longitudinal tilt, when $\epsilon = \pi/2$.

When $\gamma \neq 0$, the angle "seen" by the tiltmeter is not α but α' (the angle between $\overrightarrow{v'}$ and the XY plane). In the hypothesis that α and γ were in the Z$\overrightarrow{v'}$ plane, which is the case for small values of the misalignment, then $\alpha' = \alpha + \gamma$. From Fig. 7 it is easy to derive that the general expression for α' is

$$\alpha' = \mathrm{asin}(\cos\gamma \cdot \sin\epsilon \cdot \sin\theta + \sin\gamma \cdot \cos\theta) \tag{1}$$

α' (the angle we measure) is in fact the complementary of the angle between the tiltmeter axis and the gravity vector.

During the CMS operation we expect pure longitudinal tilts in the range $\pm$ 0.3 degrees. Eventual simultaneous transversal tilts, in the same angular range, may be present.

5 The expected effect of transversal tilts

Qualitatively, when the 1D tiltmeter is tilted transversally, the longitudinal output is expected to decrease: the output voltage of the sensor is proportional to the difference of surfaces of electrodes uncovered by the bubble. When the tiltmeter tilts transversally, depending on the relative dimensions between bubble, electrodes and the case, the bubble shifts across the electrodes, and eventually could leave them. Whatever happens, the global uncovered surface decreases and so does the output voltage (in absolute value).

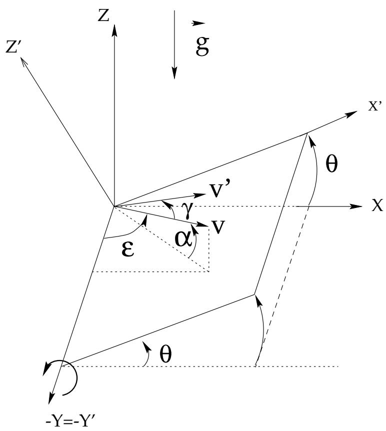

Figure 7: Angular definitions.

Fig. 8 shows the expected behaviour (in arbitrary units) of the output voltage under a transversal tilt: a sinusoidal form. The two curves correspond to different wedge angles under the sensors. Upper curve correspond to higher value of the wedge. The effect of transversal tilts increases (suppression of the output voltage) with the tilted angle. In Fig. 8 the horizontal axis represents the transversal angle moved by the tripod, while the vertical axis represents the expected output response. The difference $\alpha(\chi = 0) - \alpha(\chi = \chi_{moved})$ will be the error due to the transversal operation of the tiltmeter.

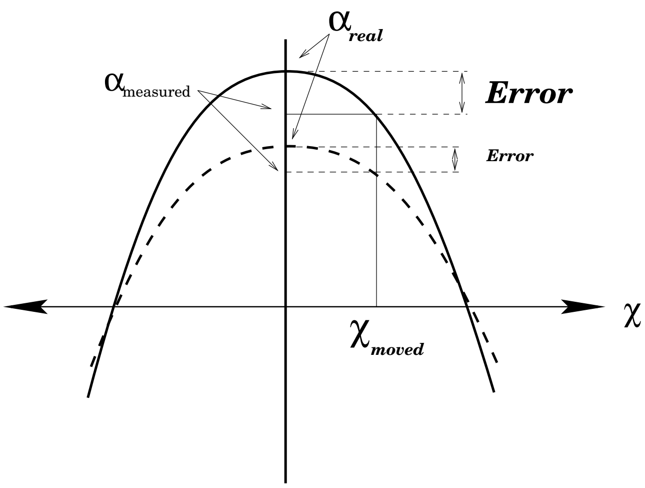

Figure 8: Expected behaviour for the output voltage of the sensors when tilted transversally. The α angle represents the longitudinal angle measured when the sensor is tilted χ transversally.

When monitoring longitudinal tilts, the measurements are affected by transversal tilts in two different ways: by the existence of a misalignment angle ϵ between the tilt and the sensor axes (as explained in Section 4) or by "real" transversal tilts.

In the first case, the transversal component is due to the mispositioning of the sensor. In the second case we include any eventual rotation around the sensor axis simultaneous with a pure longitudinal tilt.

In both cases it results in a systematic decrease in the measured output voltage leading to an underestimation of the monitored angle.

6 Longitudinal tilt: calibration

As it was said before, tiltmeters are 1D sensors. A calibration of a tiltmeter consists in finding the relation between the output voltage and the angle moved. Under a longitudinal tilt, two tiltmeters have been calibrated. Each calibration has been repeated four times.

We started the operation (see Figs. 3 and 7) by finding the position of $\theta = 0$, that would correspond to a zero value for the output voltage. From that point we tilted the sensors using the tripod in Fig. 3 from -0.3 to +0.3 degrees recording the output voltage and the Heidenhain value at each step.

No wedges were used for the calibration. γ is equal to 0 in eq. (1) and then:

$$\alpha' = \alpha = \mathrm{asin}(\sin\epsilon \cdot \sin\theta) \tag{2}$$

The angles α and θ coincide only for $\epsilon = \pi/2$. We have tried, in our set-up, to align the best we could the sensor and tripod axes.

One typical example of the sensor response (in Volts) as a function of the θ angle (in degrees) moved by the tripod is shown in Fig. 9a). It corresponds to one of the calibrations for sensor number 1.

Data points were fitted (full line in Fig. 9a)) to

$$V = V_0 + k \cdot \alpha + k' \cdot \alpha^2 \tag{3}$$

with $\epsilon = \pi/2$ in eq. (2).

We found

$$\begin{aligned} V_0 = &\quad 0.0011 \pm 0.0008 \quad \mathrm{V} \\ k = &\quad -3.900 \pm 0.0035 \quad \mathrm{V/deg} \\ k' = &\quad 0.02617 \pm 0.02491 \quad \mathrm{V/deg^2} \end{aligned}$$

The constant term V_0 shows our limitations in introducing the sensor in range (finding the zero response with the tripod). Notice that the value in our example accounts for about 0.1 % of the maximum output voltage and cannot be neglected when looking for absolute values of the tilts. The linear term is the dominant one. In the example it corresponds to a sensitivity of about 4 Volts per tilted degree. The sign of the slope indicates the sense of the tilt. The quadratic term is a correction to decrease the RMS of the residuals, increasing the precision. This term is not needed for sensor number 1 but it is absolutly necessary for sensor number 2. For uniformity, we used the quadratic expression for both sensors.

The spread of the residuals (in μrad) is shown in Fig. 9b) and distributed in Fig. 9c). They show a RMS of 3.4 μrad.

The calibration was repeated four times. The stability of the calibrations is shown in Figs. 10a), b) and c). Mean values found for V_0,k and k' are:

$$\begin{aligned} V_0 = &\quad 0.0006 \pm 0.0004 \quad \mathrm{V} \\ k = &\quad -3.8981 \pm 0.0017 \quad \mathrm{V/deg} \\ k\prime = &\quad 0.0234 \pm 0.0124 \quad \mathrm{V/deg^2} \end{aligned}$$

The distribution of the residuals (in μrad) for the four calibrations, given in Fig. 11, shows an RMS of 3.2 μrad. This corresponds to the measured resolution for sensor number 1.

The four calibrations done for sensor number 2, following identical procedure, give mean values of;

$$\begin{aligned} V_0 = &\quad 0.0020 \pm 0.0004 \quad \mathrm{V} \\ k = &\quad -3.94507 \pm 0.0017 \quad \mathrm{V/deg} \\ k\prime = &\quad 0.0875 \pm 0.0124 \quad \mathrm{V/deg^2} \end{aligned}$$

The corresponding RMS for the residuals (using the 4 calibrations) is 5.7 μrad. Although in the limit of the acceptable (we are looking for intrinsic resolutions not exceeding 5 μrad) it shows a lower quality construction than that of sensor 1.

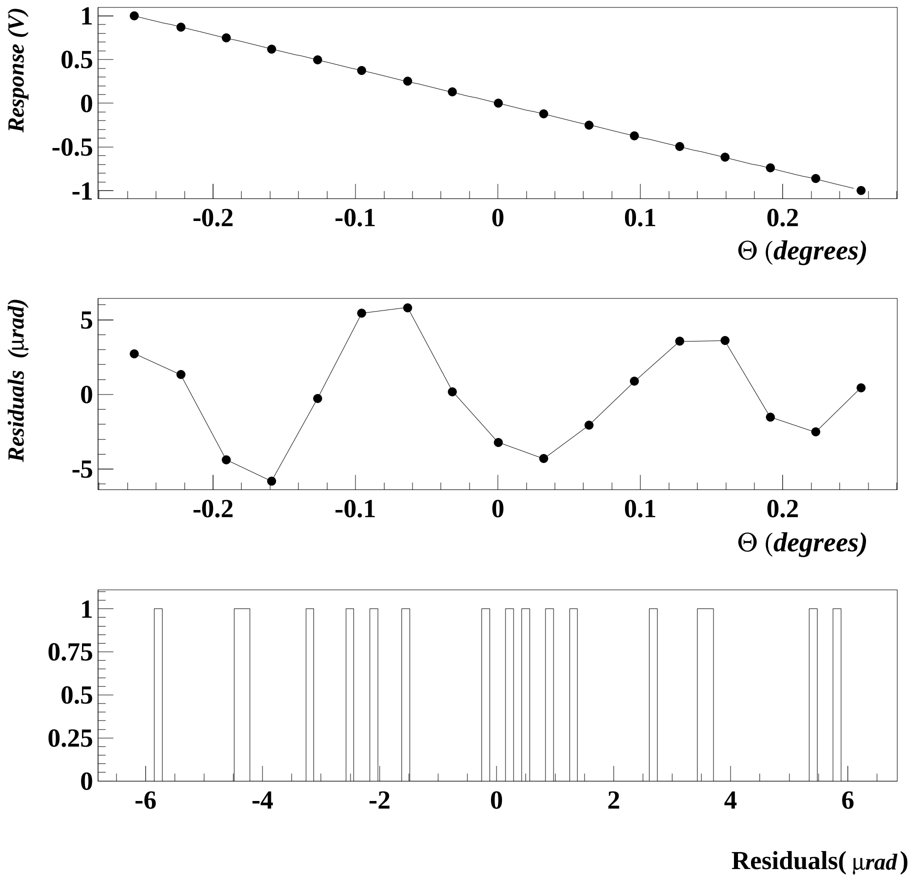

Figure 9: From a longitudinal calibration: a) Output voltage as a function of the tilt fitted to a quadratic polynomial. b) The residuals from the fit as a function of the tilt. c) The distribution of the residuals.

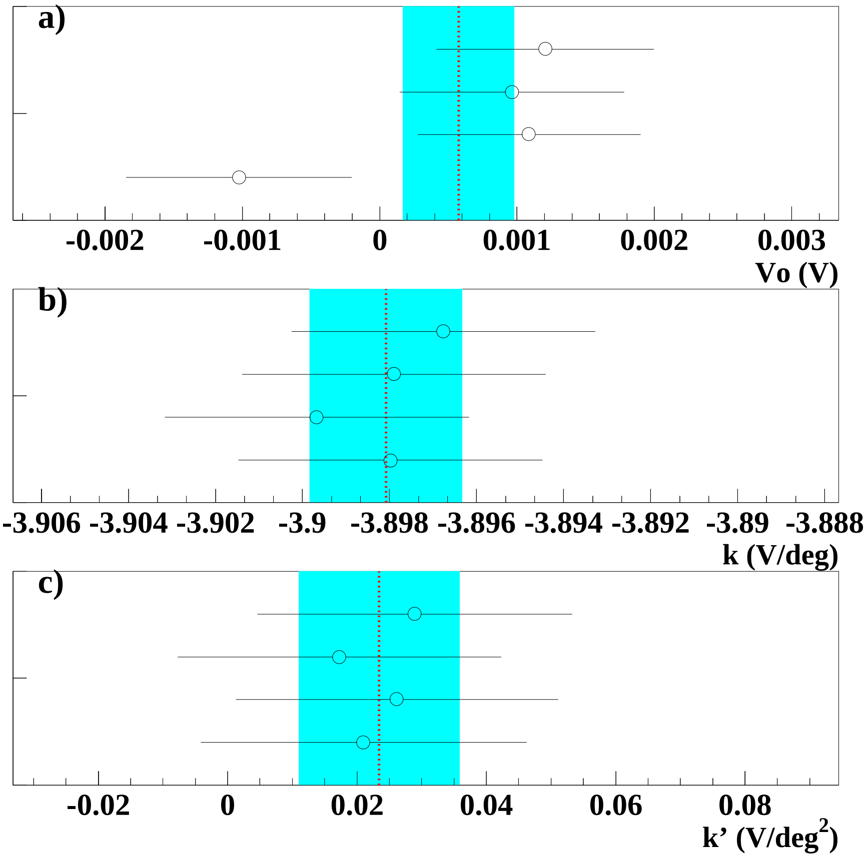

Figure 10: For the four measurements carried out (see text): a) tiltmeter offset, b) linear factor and c) quadratic term. The global average is the dotted line and the shaded area is the global rms.

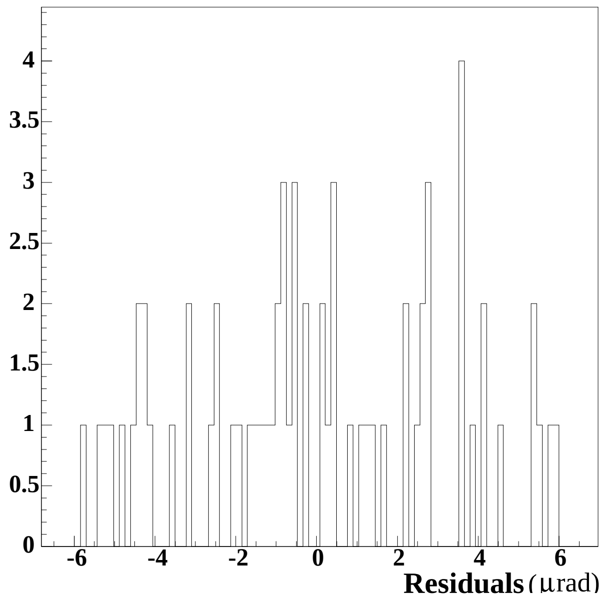

Figure 11: Projection of the residuals of a quadratic fit for sensor 1 (four experiences) discarding the ϵ contribution to the output potential.

Up to here, ϵ was considered equal to $\pi/2$ in eq.(2). We have repeated the analysis leaving ϵ free in the fits. The reproduction of the data is equally good in terms of the χ^2 and the RMS of the residuals for the full set of fits.

For sensor number 1, the mean values found were

$$\begin{aligned} V_0 &= 0.0006 \pm 0.0041 \quad \mathrm{V} \\ k &= -3.9041 \pm 0.006 \quad \mathrm{V/deg} \\ k\prime &= 0.0234 \pm 0.0126 \quad \mathrm{V/deg^2} \\ \epsilon &= 86.8 \pm 1.7 \quad deg \end{aligned}$$

From the fitting point of view there is no difference between both descriptions of the data, with ϵ equal or not to $\pi/2$. However, if there is a real misalignment of about 3.2 degrees between tilt and sensor axes, the transversal component of the tilt induced by ϵ, would induce an underestimation of the measured tilt angle due to a small suppression of the output voltage.

In first approximation, the values found for k under both hypothesis (ϵ=90 deg and ϵ=86.8 deg.) show that the underestimation of the real tilt is of the order of 0.16 %.

For the maximum expected longitudinal tilt (0.3 deg.) that would represent a systematic error of about 8 μrad, which is quite big. The alignment of the sensors with respect to the tilt axis is then a crucial issue. An unknown misorientation of a few degrees will introduce a transversal tilt component spoiling the needed resolution.

7 Measuring transversal tilts

As already pointed out, during CMS operation, eventual "pure" transversal tilts may appear. Their range will be small ($\pm$ 0.3 deg). We have tried to measure the sensor response under such tilts. The aim of the exercise is to measure the magnitude of the expected suppression of the voltage response to evaluate whether or not a monitoring of transversal tilts is necessary.

To check this point, the sensors are placed transversal to the tilt motion of the tripod and lifted by means of a wedge under one of its extremes to take it out of the stable zero state (see Fig. 12). That setup will correspond to ϵ=0 in Fig. 7.

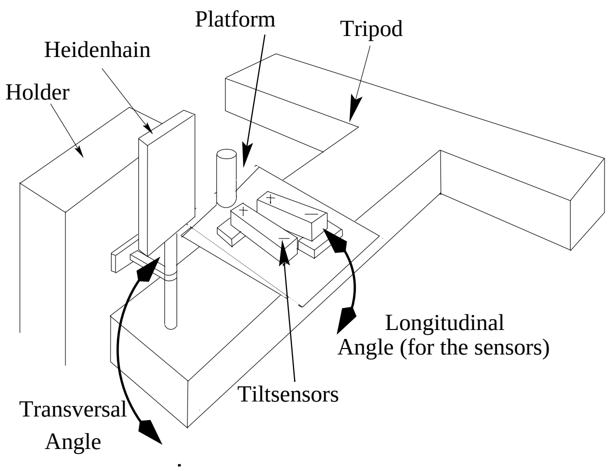

Figure 12: 3D view of the arrangement of the sensors during a transversal calibration. The sensors are lifted using wedges.

For the test, we tilted the tripod in Fig. 12, from -0.3 deg to 0.3 deg. This angle now corresponds to a transversal tilt of the sensors in the same angular range. The measured voltage as a function of the transversal tilt angle is given in Fig. 13 for sensor number 1. As one can see, the shape is not looking like in Fig. 8, but rather reminds the behaviour in Fig. 9a).

The indication seems clear: the longitudinal axis of the tiltmeter and the tilt axis of the tripod were not perfectly perpendicular ($\epsilon \neq 0$) and the small longitudinal component in the overall tilt is masking the "transversal contribution" to the output voltage. The amplitude of the output voltage is dominated by the effect of the wedge and the slope by a non zero value of ϵ.

To check above statement we have fitted the data in Fig. 13 to the quadratic expression for V (eq. (3)), leaving ϵ and γ as free parameters (eq. (1)) and using for V_0, k and $k\prime$ the mean values found during the longitudinal calibration assuming no misorientation.

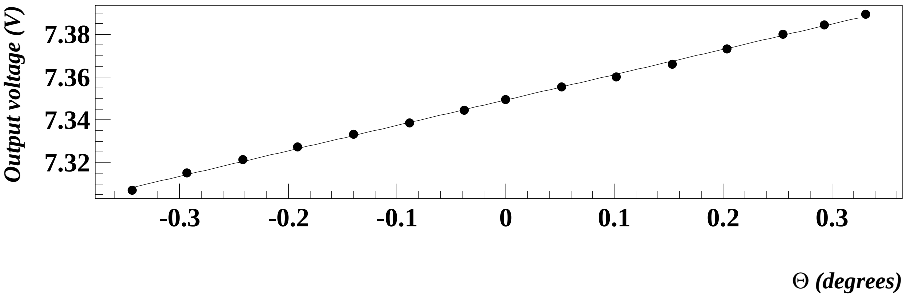

Figure 13: Output response of one of the sensors as a function of the transversal tilt (see text).

The result of the fit (continuous line in Fig. 13) were $\epsilon = 1.71 \pm 0.04$ and $\gamma = 1.86 \pm 0.01$, both values in degrees. The quality of the fit is good and the RMS of the residuals amounts for 3.3 μrad.

Data in Fig. 13 is then compatible with a misorientation of about 1.7 deg with respect to the perpendicular. The value of γ found in the fit is consistent with the wedge we put under the sensors. It was not measured in advance with precision and this is why it was left free in the fit.

To extract from the data the contribution from the pure transversal component is not possible due to the complexity of eq. (1). Nevertheless, and since we are dealing with very small angles, we have quantified the effect in first approximation by using the fitted function V(ϵ, γ, θ). Fig. 14 shows, for the various values of θ the value of the function for $\epsilon = 0$. The curve is just an interpolation between points. The behaviour corresponds to the expectations (Fig. 8). The maximum expected suppresion of the output voltage is in the 1.4×10^{-3}% inducing in the present test a systematic error well smaller than 1 μrad.

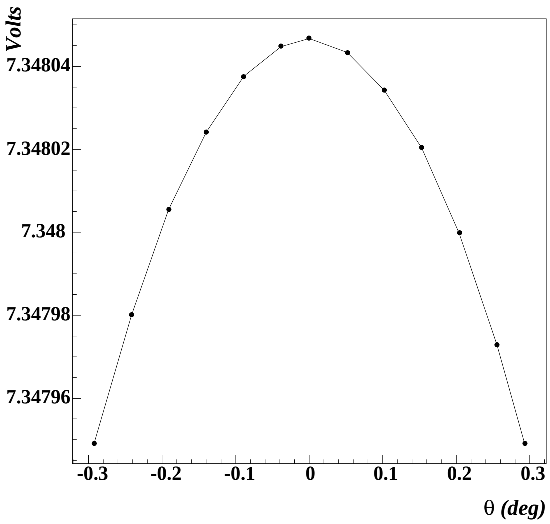

Figure 14: Example of the expected reduction of the output voltage for pure transversal tilts (see text).

8 Conclusions

Two tiltmeters have been independently calibrated and the different angles contributing to the output response have been studied. It is found that the response against longitudinal tilts can be parametrised with a second order polynomial in the tilted angle. For one of the two sensors a linear fit is sufficient, indicating a difference in the quality construction of both sensors and suggesting a possible test of quality control in a mass production.

The sensors sensitivity is found to be of about 4 Volts per arc degree.

From our experiments about longitudinal tilts, we learned that it is crucial a correct positioning of the sensor with respect to the expected tilt axis. A misorientation of about 3 degrees induces a transversal tilt that, in the expected CMS movements, may account for up to 8 μrads. This is almost twice the measured intrinsic resolution of the sensors (4-5 μrad).

From transversal tilts experiments we deduce that, in the expected range of angular movements, they can be neglected and do not need any extra monitoring.

The intrinsic resolution found, 4-5 μrad, is satisfactory for the foreseen application.

References

[1] The CMS Collaboration, ”CMS Technical Proposal”, CERN/LHCC 94-38.

[2] The CMS Collaboration, ”The Muon Project Technical Design Report”, CERN/LHCC 97-32.

[3] The CMS Collaboration, ”The Tracker Project Technical Design Report”, CERN/LHCC 98-6.

[4] Applied Geomechanics Incorporated 1336 Brommer Street Santa Cruz, CA 95062 U.S.A. The model tested in this document belongs to the 756-Series Mid-Range Miniature Tilt Sensors.