Protocol for evaluation of optical quality, thermal losses and incident angle modifier of parabolic trough concentrators

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Executive Summary

The EU-funded research project - SFERA - aims to boost scientific collaboration among the leading European research institutions in solar concentrating systems, offering European research and industry access to the best research and test infrastructures and creating a virtual European laboratory. The project incorporates the following activities:

- Transnational Access: Researchers will have access to five state-of-the-art high-flux solar research facilities, unique in Europe and in the world. Access to these facilities will help strengthen the European Research Area by opening installations to European and partner countries' scientists, thereby enhancing cooperation.

- Networking: These include the organisation of training courses and schools' to create a common training framework, providing regularised, unified training of young researchers in the capabilities and operation of concentrating solar facilities. Communication activities will seek to both strengthen relationships within the consortium, creating a culture of cooperation, and to communication to society in general, academia and especially industry what SFERA is and what services are offered.

- The Joint Research Activities aim to improve the quality and service of the existing infrastructure, extend their services and jointly achieve a common level of high scientific quality.

This deliverable is the result of the WP14 – Task 14.2 “Protocols for characterization of parabolic trough concentrators” within the Joint Research Activities.

The WP14 aims to define common protocols to be applied at the participating research infrastructures for characterization of solar concentrators.

This deliverable D14.6 “Protocol for evaluation of optical quality, thermal losses and incident angle modifier of parabolic trough concentrators” contains outdoor test methods for measuring the peak optical efficiency, incident angle modifier and heat losses of a single parabolic-trough collector unit. The methodology proposed has been tested in the test facilities available at the Plataforma Solar de Almería for qualification of complete collectors and single components of parabolic troughs.

Nomenclature

α	absorptance (-)
η_t	overall collector efficiency (-)
$\eta_{b,0}$	peak optical efficiency (-)
θ	incidence angle of solar radiation to the collector aperture plane (º)
θ_L	longitudinal incidence angle parallel to the tracking axis (º)
θ_T	transversal incidence angle perpendicular to the tracking axis (º)
ρ	reflectance (-)
$\rho_{col,max}$	maximum reflectance measured, collector's reflectors (-)
τ	transmittance (-)
γ_T	optical intercept factor (-)
$a_{1,K}$	first IAM parameter (degrees^{-1})
$a_{2,K}$	second IAM parameter (degrees^{-2})
$a_{n,K}$	*nth* IAM parameter (degrees^{-n})
b_1	first thermal losses parameter (W/K)
b_2	second thermal losses parameter (W/K^4)
c_1	heat loss coefficient at $(T_m - T_a)$ = 0 K (W/(m^2·K))
c_5	effective thermal capacity (J/(m^2·K))
c_8	radiation losses coefficient (W/(m^2·K^4))
c_p	specific heat capacity of the heat transfer fluid (J/(kg·K))
h	specific enthalpy of the heat transfer fluid (J/kg)
t	time (s)
u	wind speed (m/s)
A_C	collector aperture area (m^2)
G_b	direct normal irradiance (W/m^2)
G_{bT}	direct solar irradiance on the collector aperture plane, $G_b \cdot \cos\theta$ (W/m^2)
F_C	cleanliness factor (-)
K_b	incidence angle modifier relative to the direct incidence solar radiation (-)
$\dot{m}$	mass flow rate (kg/s)
T_a	ambient temperature (°C)

T_{in}	fluid temperature, collector inlet (°C)
T_m	average fluid temperature (°C)
T_{out}	fluid temperature, collector outlet (°C)
$\dot{Q}_{gain}$	useful power extracted from collector (W)
$\dot{Q}_{loss}$	thermal losses of collector (W)

Acronyms

CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CMS	centre of mass
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V
IAM	Incidence Angle Modifier
IEC	International Electrotechnical Committee
ISO	International Standardization Organization
PTC	parabolic-trough collector
PSA	Plataforma Solar de Almería
REPA	rotation and expansion performing assembly
RMS	root mean square
SCA	solar collector assembly
SCE	solar collector element
SDX	standard deviation on x-axis
STE	solar thermal electric

1 Introduction

This report aims at describing best practice procedures for the outdoor/ in-situ determination of the peak optical efficiency, thermal losses and the incidence angle modifier for large-size parabolic trough collectors with one-axis solar tracking. Just to make it clear, the term "large-size parabolic trough collectors" refers to collectors with concentration ratios higher than 20 and collector length equal or larger than 100 m, as the existing collectors currently installed in solar thermal electric (STE) power plants with parabolic troughs.

2 Optical and thermal performance of parabolic-trough collectors: Steady-state test method

This testing procedure allows obtaining the optical response of a parabolic trough solar collector for angles of incidence of solar radiation in the range of (0°-90°), and the thermal performance of the solar collector at various operating temperatures, when the angle of incidence of solar radiation is zero to satisfy the maximum optical response condition. The testing of a large-size parabolic trough collector (PTC) prototype is done in two stages:

- Measurement of the optical performance of the collector. It requires that the receiver tube is correctly located in the focal line of the parabolic trough when the fluid is cold, near ambient temperature. In this first stage, tests are carried out to measure the peak optical efficiency (optical efficiency with incidence angle equal to 0°) and the incidence angle modifier. Heat losses are also measured at low temperature to quantify its influence (Valenzuela, 2014).

- Measurement of the thermal performance of the collector. It requires that the receiver tube is correctly located in the focal line of the parabolic trough when the fluid temperature is within the (high) temperature working range, e.g. between 293°C and 393°C (for current commercial STE power plants with thermal oil as heat transfer fluid). Tests are carried out at different fluid temperatures within the operational range to measure the thermal efficiency when the angle of incidence of solar radiation is 0°, which e.g. occurs at the solar noon for parabolic-trough collectors oriented in East-West direction.

2.1 Basic concepts

The energy balance in a parabolic-trough collector can be expressed with the following equation:

Equation 1 $$\dot{m} \cdot \Delta h = A_C \cdot G_{bT} \cdot \eta_{b,0} \cdot K(\theta) \cdot F_c - \dot{Q}_{loss}$$

where $\dot{m}$ is the mass flow rate (in kg/s), Δh is the increase of the specific enthalpy experimented by the fluid in the collector (in J/kg), A_C is the net collecting area of the collector (in m^2), G_{bT} is the direct radiation on the collector aperture plane (in W/m^2), $\eta_{b,0}$ is the peak optical efficiency (-), θ is the incidence angle (in degrees), $K(\theta)$ is the incidence angle modifier (-), F_c is the collector cleanliness factor (-), and $\dot{Q}_{loss}$ represents the thermal losses of the collector (in J/s). The direct solar irradiance on the collector aperture plane G_{bT} is calculated as $G_b \cdot \cos\theta$ where G_b is the direct solar irradiance measured with a pyrheliometer.

The longitudinal plane (index L) runs parallel to the optical axis of the solar collector, and the transversal plane (index T) is perpendicular to the optical axis. Angles θ_L and θ_T are the projections of the incidence angle θ on the longitudinal and transversal planes respectively (see Figure 1).

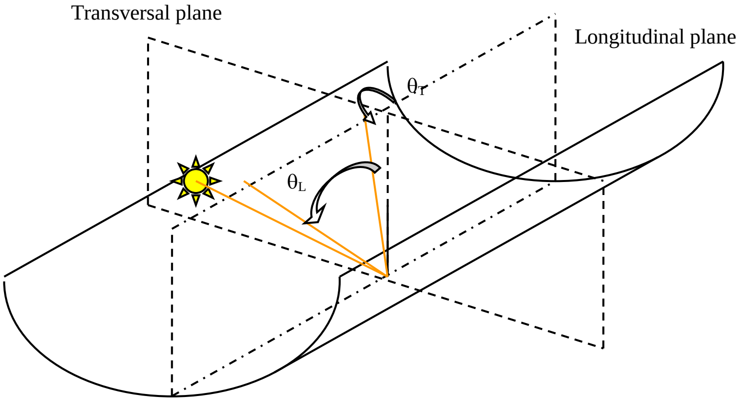

Figure 1. Longitudinal and transversal projections of the incidence angle of solar radiation in a parabolic-trough collector.

The following equation is used to establish the correlation among the angles θ,θ_L and θ_T:

Equation 2 $$\boldsymbol{tan^2\theta = tan^2\theta_L + tan^2\theta_T}$$

For those parabolic-trough collectors where the effects of the incidence angle are not symmetric with regard to the incidence direction, it is necessary to measure the effects of the incidence angle in the longitudinal plane, θ_L, to characterize the incidence angle modifier. In the transversal plane a solar tracking will be used to adjust continuously the transversal incidence angle, θ_T, to 0º.

Note: The collector cleanliness factor F_C must be taken into consideration in every sequence of the test.

2.2 Instrumentation

Because a large confidence interval is desired in the data treatment of results, uncertainties of measurements are multiplied by a coverage factor *k* = 2) to provide an uncertainty range that is believed to include the true value with a confidence of 95% (2*standard deviation, assuming the set of measurements of a particular measurand follows a normal distribution). For more details see (GUM, 1995).

2.2.1 Direct solar radiation

Direct solar radiation is measured with a pyrheliometer mounted on a separate solar tracking device. The pyrheliometer field of vision will be no more than 6º of arc. This instrument will be of “first class” according to the ISO 9060 regulation and will be directly calibrated with traceability to a primary pyrheliometer of reference. The equipment will be recalibrated at least once a year. The accuracy after recalibration must be higher than ±1.0 % of the average value applying the appropriate linearity and temperature corrections. The tracking errors associated to the mounting on the tracker must not exceed ±0.7º (SFERA, 2013).

2.2.2 Flow

The mass flow rate of the heat transfer fluid ($\dot{m}$) will be determined with an accuracy higher than ±1.0 % of the average value for each measuring point within the range.

In general, the use of a mass flow meter of the Coriolis ty is recommended, instead of volumetric flow meters due the better accuracy offered by the former ones and their no extra uncertainty associated due to the uncertainty of the heat transfer fluid density.

The flow meter used will be according to ISO 9806:2013.

2.2.3 Temperature

Tthe temperature of the fluid must be measured at the inlet and outlet of the solar collector. The ambient temperature is also needed. The requirements for the sensors and auxiliary equipment are different, due to the differences in the measurement temperature range and in the installation of the sensors.

In any case, it is recommended to use PT100 thermoresistance, Class A accuracy, connected using 4-wire connection to reduce the influence of wire voltage fluctuation in the temperature measurement.

The sensor used will be according to ISO 9806:2013, but requirements for the accuracy can be different (less restrictive) due to the higher temperature working conditions of large-size parabolic trough collectors.

2.2.4 Wind speed

The wind speed in the horizontal plane will be determined with an accuracy higher than ±0.5 m/s for each point measured and it will be less than 5 m/s during the tests performed to determine the peak optical efficiency or the incidence angle modifier. The sensor should be installed at a height of about 10 m and close to the test site (distance less than 100 m) (IEC TC117, 2017).

2.2.5 Solar tracking and incidence angle

Any solar tracking used different to that of the manufacturer must have a tracking error no more than ± 0.1º in all main angles of the collector.

Incidence angles will be determined by calculation or with sun position sensors with accuracy equal or higher than ± 0.1º.

Please refer to Section 4 for the characterization of the solar tracking angle with inclinometers.

2.2.6 Data acquisition system

Sampling of all variables relevant to the test must be performed in 5 seconds interval maximum, in such a way that the radiation stability and fluid temperature can be controlled in a quasi-steady period, before and after the test.

A measuring point will be the average of all values measured of one variable taken in an interval of no more than 30 seconds.

2.2.7 Collector soiling (reflector and receiver glass envelope)

During characterization tests of a parabolic-trough collector it is necessary to guarantee that the reflectors and glass envelopes of the receivers are completely clean. For that it must be taken into consideration that the collector's cleanliness factor is within the range 0.95 < F_C < 1.0. The cleanliness factor is defined as the ratio between the product of the reflectors reflectance and the glass envelope transmittance during the test and the product of the reflectance and nominal transmittance. So far there is no field instrumentation available to determine the degree of soiling on the receiver glass envelope. A good approach is to calculate the cleanliness factor applying Equation **3** (Janotte, 2014).

Equation 3 $$\boldsymbol{F_C} = \left(\frac{\rho}{\rho_{col,max}}\right)^{3/2}$$

It is recommended to measure the reflectors reflectance ρ with a portable reflectometer in each sequence of the test. Details on the reflectance measurement procedure may be found in (SolarPACES, 2013). Once the reflectors and receiver tubes are installed in a collector, it is assumed as a good approach that the same percentage of reduction in the reflectors reflectance and in transmittance of the glass envelope is produced due to dirt.

2.3 Test procedure

During tests, it must be guaranteed that the receiver is positioned in the focal line through the parabolic-trough collector, including the ends, to ensure that the intercept factor is maximal.

2.3.1 Peak optical efficiency

While the collector is kept in normal incidence, the inlet fluid temperature T_{in} must be kept steady and as close as possible to T_a to minimize heat losses, the transversal incidence angle at $\theta_T = 0° \pm 0.1°$ and the longitudinal incidence angle to measure $\theta_L \pm 0.1°$.

The stability of the measurements and other requirements of table 1 will be controlled.

The measurement is carried out at least 3 times. Additional measurements may be necessary depending on the uncertainty level calculated.

If during these tests the inlet fluid temperature is higher than $T_a + 20\ \mathrm{K}$, the heat losses produced in the collector must be measured in different runs within the low temperature range, where it is foreseen to perform the peak optical efficiency tests.

A "measurement point" will be the mean of measures read in an interval of at least 5 minutes or the average time constant -if it is known-, fulfilling the quasi-steady conditions.

Table 1. Peak optical efficiency test: requirements for quasi-steady conditions.

Parameters to be controlled	**Permitted deviation from the mean**
Inlet fluid temperature, T_{in}	± 0.5 K
Increase of fluid temperature, $(T_{out} - T_{in})$	± 0.5 K or 4.0%
Mass flow rate, $\dot{m}$	± 1.0%
Direct solar radiation, G_b	± 40 W/m^2
Ambient temperature, T_a	± 1.0 K
Threshold levels (additional conditions)	**Limit**
Direct solar radiation, G_b	> 800 W/m^2
Longitudinal indicence angle, $\Delta\,\theta_L$	< 5°
Transversal incidence angle, $\Delta\,\theta_T$	± 0.1°
Wind speed, u	< 5 m/s
Collector cleanliness factor, F_c	> 0.95

2.3.2 Incidence angle modifier (IAM)

While the collector is kept at a specific longitudinal incidence angle θ_L, the inlet temperature of the fluid T_{in} must be kept constant and as close as possible to $T_a \pm 1\ \mathrm{K}$ to minimize heat losses, the transversal incidence angle to $\theta_T = 0° \pm 0.1°$ and the longitudinal incidence angle measuring $\theta_L \pm 2°$.

The stability in the measurements and other requirements of Table 2 are to be observed.

At least 10 incidence angles up to the maximum angle $\theta_{L,max}$ must be measured following the same procedure. $\theta_{L,max}$ will be 70º at least, unless the manufacturer specifies a different value. Every angle will be measured at least twice.

Intermediate angles will be equidistance between 0º and $\theta_{L,max}$. If the tests of incidence angle modifier are performed in different days, then it should be necessary to repeat the measurement and evaluation of the reference efficiency for $\theta_L = 0°$ every day to minimize the effects of variations in meteorological conditions.

Table 2. Incidence angle modifier test: requirements for quasi-steady conditions.

Parameters to be controlled	Permitted deviation from the mean
Inlet fluid temperature, T_{in}	± 0.5 K
Increase of fluid temperature, $(T_{out} - T_{in})$	± 0.5 K or 4.0% for $\theta_L \leq 40°$ ± 1.0 K for $\theta_L > 40°$
Mass flow rate, $\dot{m}$	± 1.0%
Direct solar radiation, G_b	± 40 W/m^2
Ambient temperature, T_a	± 1.0 K
Threshold levels (additional conditions)	**Limit**
Direct solar radiation on the aperture plane, G_{bT}	$> 800 * \cos\theta$ W/m^2
Longitudinal indicence angle, $\Delta\theta_L$	± 2.0°
Transversal incidence angle, $\Delta\theta_T$	± 0.1°
Wind speed, u	< 5 m/s
Collector cleanliness factor, F_c	> 0.95

NOTE: For checking the symmetry of the IAM characteristic of the collector, it is advised to measure the same angle in the morning and afternoon.

NOTE: for North-South orientation (East-West tracking) this test can be too long to gather the incidence angles required. In this case a minimum direct radiation of $G_{bT} > 600 * \cos\theta$ W/m^2 may be accepted.

2.3.3 Heat losses (method off track collector)

To determine the heat losses, the collector is defocused to avoid the incidence of direct radiation or even global or diffuse radiation on the reflecting surface and receiver (for this reason the tests are carried out preferentially on cloudy days or at night-time). During the test, a constant flow of heat transfer fluid is circulating through the collector; the inlet fluid temperature T_{in} is maintained constant and within the operation range. The system must be preheated prior to the recording of any measuring point, fulfilling the quasi-steady conditions. It is advisable to obtain the value of heat losses for at least 4 different values of inlet temperature T_{in} in the operational range.

A "measurement point" will be the mean of measures read in an interval of at least 10 minutes or the average time constant -if it is known-, fulfilling the quasi-steady conditions listed in Table 3.

2.3.4 Heat losses (alternative method by means of overall collector efficiency measurement)

NOTE: This method can be used in case of no night tests.

During the test, the inlet fluid temperature T_{in} must be kept constant in a value defined within the normal working temperature range of the collector. It is also recommended to perform the test with the collector in normal incidence, i.e. assuring that $\theta_L \pm 0.1°$ and $\theta_T = 0° \pm 0.1°$.

Stability of the measurements and other requirements of the table 4 will be controlled.

Overall collector efficiency will be measured at least 3 times for every value of inlet temperature T_{in} defined. Tests will be performed for at least 4 values of different inlet temperatures and equidistant in the range of normal working temperature of the collector.

Table 3. Heat losses test (off track collector): requirements for quasi-steady conditions.

Parameters to be controlled	**Permitted deviation from the mean**
Inlet fluid temperature, T_{in}	± 0.5 K
Increase of fluid temperature, $(T_{out} - T_{in})$	± 0.5 K or 4.0%
Mass flow, $\dot{m}$	± 1.0%
Ambient temperature, T_a	± 1.0 K
Threshold levels (additional conditions)	**Limit**
Direct solar radiation, G_b	< 100 W/m^2
Wind speed, u	< 5.5 m/s

Table 4. Heat losses test (overall efficiency method): requirements for quasi-steady conditions.

Parameters to be controlled	**Permitted deviation from the mean**
Inlet fluid temperature, T_{in}	± 0.5 K
Increase of fluid temperature, $(T_{out} - T_{in})$	± 0.5 K or 4.0% for $\theta_L \leq 40°$ ± 1.0 K for $\theta_L > 40°$
Mass flow, $\dot{m}$	± 1.0%
Direct solar radiation, G_b	± 40 W/m^2
Ambient temperature, T_a	± 1.0 K
Threshold levels (additional conditions)	**Limit**
Direct solar radiation, G_b	$> 800 * \cos\theta$ W/m^2
Longitudinal indicence angle, $\Delta\theta_L$	± 2.0°
Transversal incidence angle, $\Delta\theta_T$	± 0.1°
Wind speed, u	< 5 m/s
Collector cleanliness factor, F_c	> 0.95

2.4 Calculations and results

2.4.1 Peak optical efficiency

The value of peak optical efficiency is calculated as follows:

Equation 4 $$\eta_{b,0} = \frac{\dot{m} \cdot \Delta h - \dot{Q}_{loss}}{A_c \cdot G_{bT}}$$

The incidence angle modifier and the cosine factor are assumed to be equal to 1 because the tests are carried out at normal incidence ($\theta_L = 0°$).

The value of the collector peak optical efficiency is obtained from the average of at least 3 measurements of peak optical efficiency, which are calculated according to Equation 4.

2.4.2 Incidence angle modifier (IAM)

The value of the incidence angle modifier, $K(\theta)$, is obtained from Equation 1 and the result of the peak optical efficiency calculated according to Equation 4. The set of values $K(\theta)$ obtained as a function of the different incidence angles θ may be fitted by a curve type as this:

Equation 5 $$K(\theta) = 1 - \frac{a_{1,K} \cdot \theta + a_{2,K} \cdot \theta^2 + .. + a_{n,K} \cdot \theta^n}{\cos\theta}$$

Where parameters $a_{1,K}$, $a_{2,K}$, …, $a_{n,K}$ are determined by means of least-squares fit.

Collector end losses are included in the IAM in this approach.

2.4.3 Heat losses (method off track collector)

The value of thermal losses $\dot{Q}_{loss}$ is determined from Equation 1, considering tests conditions that allows to void the first summand from the right side of this equation, so it is possible to calculate the value of those losses as a function of the fluid flow that circulates through the collector and the decrease in the fluid enthalpy between the inlet and outlet of the collector. The resulting set of heat loss results in the test temperature range can be approximated by an expression of the type:

Equation 6 $$\dot{Q}_{\text{loss}} = b_1 \cdot (T_m - T_a) + b_2 \cdot (T_m - T_a)^4$$

Where b_1 and b_2 are the coefficients (in W/K and W/K^4 respectively) of the polynomial fit. The increase of enthalpy experimented by the fluid is calculated as $\Delta h = h_{out} - h_{in}$, but provided no phase change and nearly constant pressure in the system this simplifies as:

Equation 7 $$\Delta h = \int_{T_{in}}^{T_{out}} c_p \cdot dT$$

Where c_p is the specific heat capacity at constant fluid pressure (J/kg/K), which directly depends on the fluid temperature. The specific heat capacity values may be got from HTF manufacturer's datasheet or by testing samples of heat transfer fluid in an accredited laboratory.

2.4.4 Heat losses (alternative method by global efficiency)

The value of overall collector efficiency is calculated as follows:

Equation 8 $$\eta_t = \frac{\dot{m} \cdot \Delta h}{A_c \cdot G_{bT}}$$

Recommended test conditions are to run the experiments with normal incidence of solar radiation ($\theta_L = 0°$), which assures that the cosine of the incidence angle and the incidence angle modifier are equal to 1.

The overall efficiency of the collector for each temperature level is obtained by measuring at least 3 points of global efficiency obtained applying Equation 8.

The overall efficiency for the whole working temperature range of the collector must be adjusted applying least squares method to a curve type:

Equation 9 $$\eta_{t,0} = \eta_{b,0} - \frac{b_1 \cdot (T_m - T_a) + b_2 \cdot (T_m - T_a)^4}{A_c \cdot G_{bT}}$$

The heat losses in the working temperature range can also be obtained from this adjustment.

2.4.5 Validation: overall efficiency result

To validate the result of overall collector efficiency, it is proposed to run additional tests to record data while the collector is kept in operation for two days at two different constant values of inlet fluid temperature T_{in} within the normal working temperature range of the collector. During these tests, the transversal incidence angle must be $\theta_T = 0° \pm 0.1°$ and the longitudinal incidence angle θ_L varies from 0º to 60º during the whole day.

Stability of the measurements and other requirements of the former overall efficiency table (see Table 4) will be controlled.

To validate the former characterization, the overall efficiency must be calculated according to equation 10, which is similar to equation 9 but also accounts for the incidence angle modifier (Equation 5), the cleanliness factor F_c, and the cosine of the incidence angle θ.

Equation 10 $$\eta_t = \eta_{b,0} \cdot K(\theta) \cdot F_c - \frac{b_1 \cdot (T_m - T_a) + b_2 \cdot (T_m - T_a)^4}{A_c \cdot G_{bT}}$$

The deviation between the calculated (Equation 10) and measured (Equation 8) efficiency should be less than ±5%.

2.4.6 Validation: peak optical efficiency

With regard to the peak optical efficiency and for assuring that experimental results from the outdoor testing are valid, a cross check with single parameters available for each solar component of the whole collector can be performed.

From the intercept factor measured (by deflectometry, photogrammetry, or others techniques), the optical properties (reflectance of the reflector, and transmittance of glass envelope and absorptance of the absorber tube provided by the receiver and reflector manufacturers), the peak optical efficiency can be calculated using the following expression:

Equation 11 $$\eta_{b,0} = \gamma_T \cdot \rho \cdot \tau \cdot \alpha$$

Where γ_T is the intercept factor of the collector, which also accounts for the effective length of the receiver tubes, ρ is the solar weighted reflectance of the mirrors, τ is the transmittance of the glass envelope, and α is the absorptance of the absorber tube. Using the nominal values offered by the suppliers or measured directly on-site with other methods different to the ones presented in this document, it is possible to do a cross check of the results obtained applying Equation 4 and Equation 11.

The deviation between the calculated (Equation 11) and measured (Equation 4) optical efficiency should be less than ±5%.This value is an estimate and will depend on how much accurate are the values of components properties used. If a high deviation is found, both each single component parameter and the results of the experimental test should be revised to look for the reason.

3 Optical and thermal performance of parabolic-trough collectors: Quasi-dynamic test method

This testing procedure corresponds to the quasi-dynamic testing method proposed in the standard ISO9806:2013 but including modifications related to the consideration of the cleanliness factor F_c during the parameters identification process, and the incorporation of an alternative parameter c_8 instead of c_2, which is also related to temperature dependence of heat loss.

3.1.1 Basic concepts

For the quasi-dynamic testing method, the following equation is applied:

Equation 12 $$\frac{\dot{Q}_{gain}}{A_C} = \eta_{0,b} \cdot K_b(\theta) \cdot G_{bT} \cdot F_c - c_1 \cdot (T_m - T_a) - c_8 \cdot (T_m - T_a)^4 - c_5 \cdot \frac{\partial T_m}{\partial t}$$

where $\dot{Q}_{gain}$ is the power gained by the fluid in the collector (in W), T_m is the mean fluid temperature (in °C), T_a is the ambient temperature (in °C), t is the time (in s), c_1 is the heat loss coefficient at $(T_m - T_a) = 0$ (in W/(m^2·K)), c_8 is the temperature dependence of heat loss (in W/(m^2·K^4)), $\boldsymbol{c_5}$ is the effective thermal capacitance of the system (in J/m^2·K). Equation 12 is a simplification of the equation included in ISO9803:2013 [2] for quasi-dynamic testing of solar collectors**,** which also includes modifications on terms related to optical efficiency (Janotte, 2014) and changes in temperature dependence of heat loss (Sallaberry, 2017), as previously mentioned. The influence of diffuse solar radiation and wind speed is neglected in this approach to characterize the performance of this tracking collector system.

3.2 Test procedure

A set of data points shall be obtained for at least four fluid inlet temperatures spaced over the operating temperature range of the parabolic-trough collector.

The change in inlet temperature shall be done after each test sequence has been completed. Data recorded during this “step-change” period shall not be included in the test data. The inlet temperature shall be kept stable within ± 1 K during each test sequence (ISO, 2013).

Data recorded during the quasi-dynamic testing are similar to the steady-state testing, i.e. direct solar irradiance on the collector aperture, angle of incidence of solar radiation, temperature of the ambient air, temperature of the heat transfer fluid at the inlet and the outlet, flow rate of the heat transfer fluid at the collector inlet, and wind speed.

The test procedure is the one proposed in section 23.6.2 of ISO9806:2013 (ISO, 2013).

3.3 Calculations and results

The useful power collected by the heat transfer fluid is measured as

Equation 13 $$\dot{Q}_{gain} = \dot{m} * \Delta h$$

The solar energy intercepted on the collector is $A_C \cdot G_{bT}$. The extracted power $\dot{Q}_{gain}$ is modelled applying Equation 12.

NOTE: If steady-state and quasi-dynamic testing methods are applied during the testing of a parabolic-trough collector, characteristic optical parameters, $\eta_{0,b}$ and $K_b(\theta)$, obtained applying both methodologies should be similar. In the case of parameters related to heat losses, it may be also checked the equivalence between b_1 and c_1 ($c_1 = b_1/A_C$) and between b_2 and c_8 ($c_8 = b_2/A_C$).

4 Measurement of transversal incidence angle

This section provides information on characterization of the orientation of the optical axis of each SCE, which refers to a characterization of the collector's ability to accurately follow the sun and harness the maximum radiation.

4.1 Motivation

The transversal incidence angle θ_T relative to the incoming radiation of each SCE is an important parameter during performance test. Any situation, where for a single SCE:

$$|\theta_T| > 0$$

will be denoted "tracking deviation" in following. The tracking deviation may vary within the SCA, as the individual orientation of each SCE is subject to:

- The orientation provided by the drive system
- The alignment between SCEs during installation
- The twist/torsion due to operational loads like
    - Friction (from bearings and/or REPAs)
    - Wind
    - Unbalance (mismatch of axis of rotation and centre of mass)

Tracking deviation may strongly influence the intercept factor and thus the optical and finally the thermal performance, as depicted in Figure 2.

For this reason, the knowledge about the θ_T for each SCE during thermal performance test is mandatory. This section provides a protocol for the selection and calibration of the instruments, the preparation of the measurement set-up, and some information on the evaluation.

There are several and distinct objectives for tracking characterization, which differ in terms of absolute or relative measurements, determination of the torsion stiffness, and determination of the assembly accuracy. These possibilities are described in the following

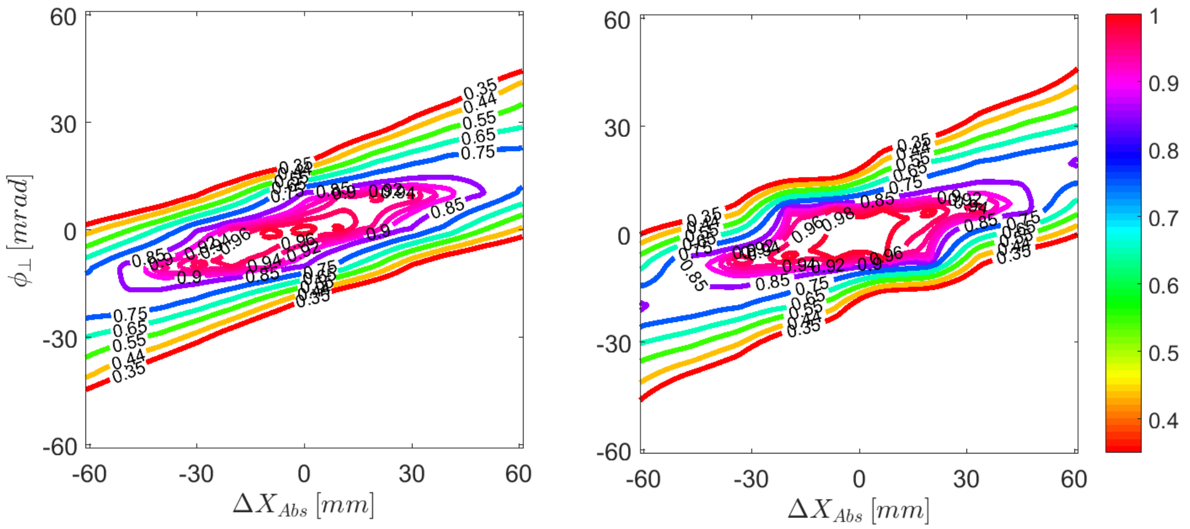

Figure 2. Ray-tracing based sensitivity analysis derived with a Circum-Solar-Ratio (CSR) of 0.05 of the intercept factor for different transversal incidence angle, different lateral deviation of the absorber from the focal line, and mirror shapes. The left graph shows results for a real RP3 concentrator with an RMS_{SDX} of 2.1 mrad. The graph on the right side is based on an ideal mirror. Transversal incidence angle and different lateral deviation of the absorber from the focal line may compensate or boost each other. The impact of 1 mrad of $\boldsymbol{\theta_T}$ is comparable to 2 mm of absorber tube deviation in a certain range. However, the intercept factor drops significantly after some 10-15 mrad. Higher RMS_{SDX} causes a wider beam spread, so that the sensitivity of the intercept factor on $\boldsymbol{\theta_T}$ is slightly decreased compared to the ideal mirror geometry.

4.2 Measurement modes and objectives

4.2.1 SCE torsion stiffness

Measurement of the SCE's torsion stiffness (described by a torsion spring constant) is performed by applying a stepwise increasing torque at the REP of the outermost SCE of an SCA and simultaneously measuring the relative twist at different positions within the SCA with digital inclinometers. Since only relative values are of interest, the mounting of the inclinometers to the SCE end-plates can be performed with comparatively little effort, as the accurate arrangement with respect to the X-axis is not required. The inclinometers can be mounted to the endplates by means of magnetic adapters and strain reliefs (see Figure 3) to assure safe measurements.

Figure 3. displays the required set-up to introduce a torque of adequate magnitude to twist the SCE. The maximum torque must be selected carefully. Using sensitive sensors reduces drastically the required signal and such the involved loads on the collector. With high grade sensors, a (twist-) signal of several milliradians is sufficient, resulting typically in applied torques in the range of 2-3 kNm. This measurement can be carried out in any orientation of the collector.

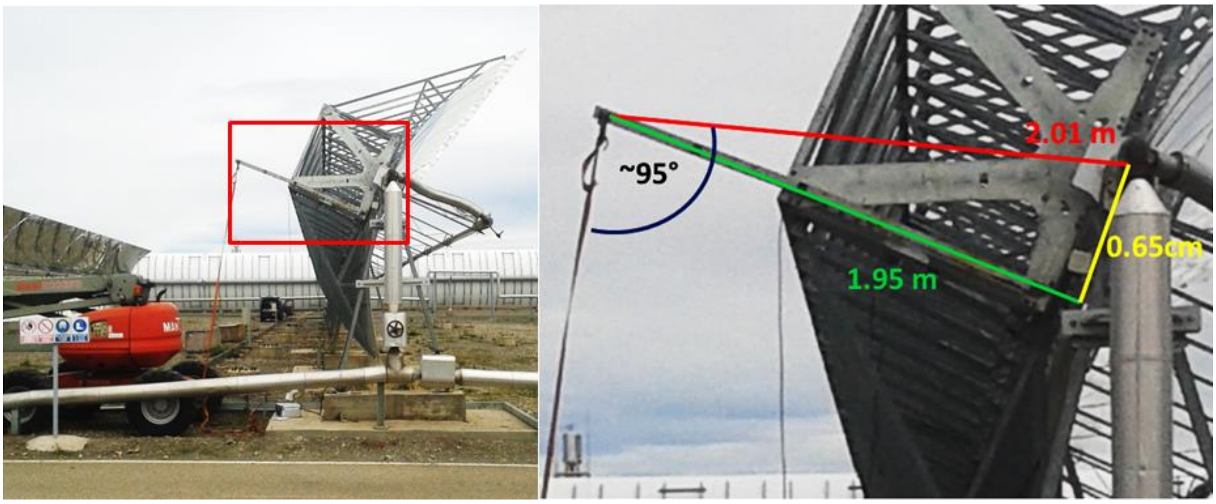

Figure 3. Set-up for the measurement of torsion stiffness: the lever attached to the REP of the last outermost SCE serves to impinge increasing torque for the measurement of torsion stiffness. A securing strap with integrated force meter is used to pull down the lever.

Assuming a linear behaviour between applied torque and observed twist, the target figure is obtained by linear regression. The results of this measurement can be used to model the response of the SCA as a mechanical system on external (wind) or internal (friction, unbalance) loads.

A result for such a torsion stiffness measurement from the first EuroTrough Collector erected at PSA is presented in Figure 4.

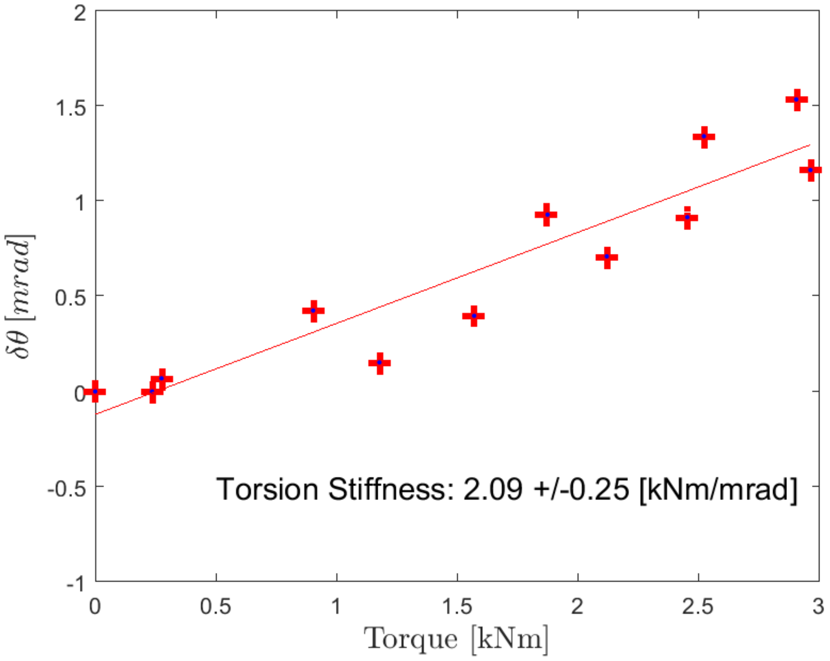

Figure 4. Results of the linear regression to determine the SCE torsion stiffness. The rather high relative uncertainty of the result is caused by the fact that the data was taken is from to successive measurements with different boundary conditions. Wind and friction affect the measurement and may lead to a slight variance of successive measurements.

4.2.2 Inter-SCE alignment (static)

The measurement and adjustment of inter-SCE alignment is normally carried out during assembly of the solar field to assure the correct orientation of the SCEs. Retrospective alignment may be required in some cases to optimize the performance. As a reference axis, a virtual axis perpendicular to the optical axis is required. This axis is commonly denoted water-level or X-axis, since it is assumed to exactly horizontal when the parabolic-trough collector is pointing upwards in Zenith position. For some collectors, there are reference drillings in the end-plates, which can be used. Since measurement uncertainty decreases with increasing distance between reference points, it might advantageous to use the outer mirror edge, assuming an accurate assembly of the mirrors of the SCE itself.

For this measurement, the inclinometers must be mounted to an adapter with sufficient dimensions to be placed on the reference drillings or the mirror edge. This adapter itself must be carefully calibrated by means of so called “turned-around” – measurements on a horizontal reference object. This way, calibration values for the specific inclinometer-adapter combination are obtained. This calibration values are indispensable to measure absolute orientations.

These measurements must be carried out in zenith position (90° +/- 1°).

4.2.3 Twist under operational loads

The parabolic through collector is twisted during the operation due to the external loads. These loads are:

- Static unbalance: Misalignment between axis of rotation and the Centre of Mass (CMS) of the parabolic trough cause a tracking angle dependent torque.
- Friction of bearings and REPAs: Friction of the support bearings and the flexible tube connectors create a torque contrary to the direction of motion
- Wind: wind forces may also create significant operational loads depending on wind direction, orientation of the parabolic trough and position of the trough within the field

The characterization of the twist due to the first two loads can be determined straight-forwards from measurement of the relative orientation of SCEs within one SCA. For this purpose, the SCA is tracked from a certain angle to another, and back to the initial position. The SCA tracking path must be contained in the measurement range of the inclinometers system. The common inclinometers measurement range is below the 180º. Although, arranging different units per SCE in series, at a specific angle each one, this range can be increased. Also a single unit per SCE performing consecutive measurements at complementary angles can be used, adjusting its relative position within the measurement range when necessary. At each tracking step, the motion is stopped for several seconds to enable the inclinometer read-out without synchronization problems. A simulated result curve of this measurement is shown in Figure 5. :

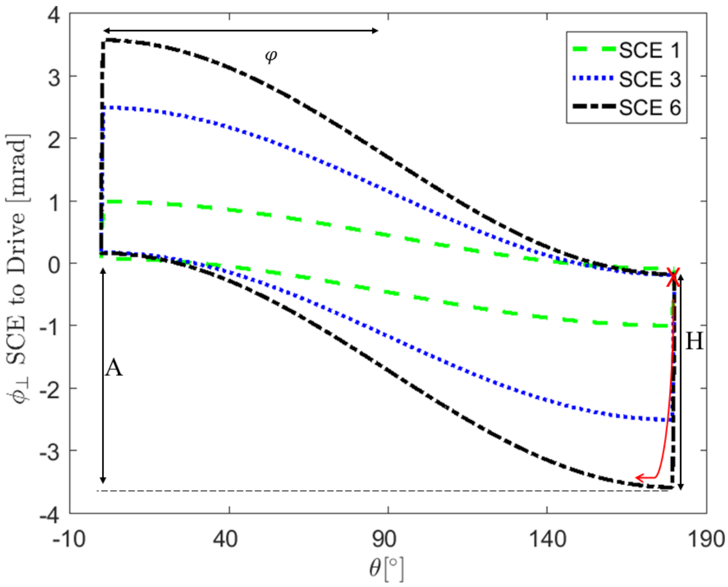

Figure 5. Simulated tracking deviation of each SCE relative to the drive pylon. The red cross and arrow mark the starting point and motion direction. The largest tracking deviation appears at the outer SCE. Friction can be directly observed from the hysteresis H, while the sinus curve is caused by the unbalance. The phase shift φ and the amplitude A are determined by the location of the CMS relative to the axis of rotation.

As mentioned the response of the parabolic trough on external loads can be measured with a multi-unit per SCE inclinometer system or with a single unit per SCE inclinometers system. In both cases the same inclinometer set-up as described in Section 4.2.1 can be used.

Figure 6 shows the results from a quasi-continuous tracking from 0º to 180º, from a multi-unit per SCE inclinometer system, and Figure 7 show the measurement results from a continuous tracking during 5º at complementary angles (from 0-5º, 45º-50º and 90-95º), for a single unit per SCE inclinometers system. In these cases a pair of inclinometers was installed in the SCA, one in the first SCE next to the drive and the other in the farther one.

As can be seen with both types of measurements system it is possible to identify the hysteresis and the sinus curve.

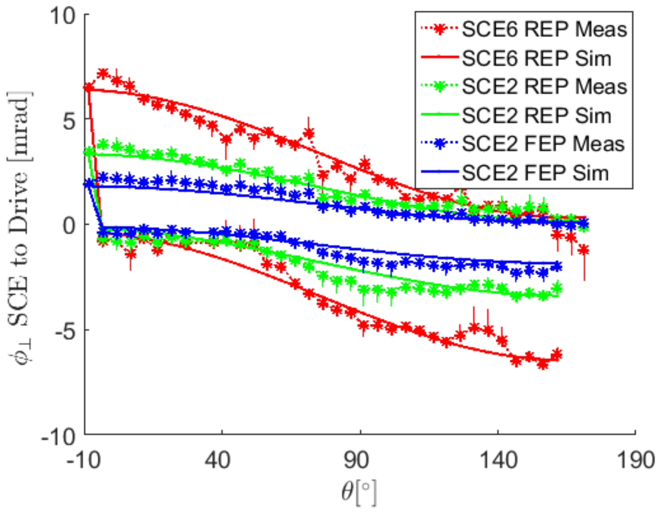

Figure 6. Measured relative twist and simulated behaviour of SCEs of the EuroTrough Prototype at PSA. Each curve shows the simulated and measured hysteresis of the tracking deviation relative to the drive pylon.

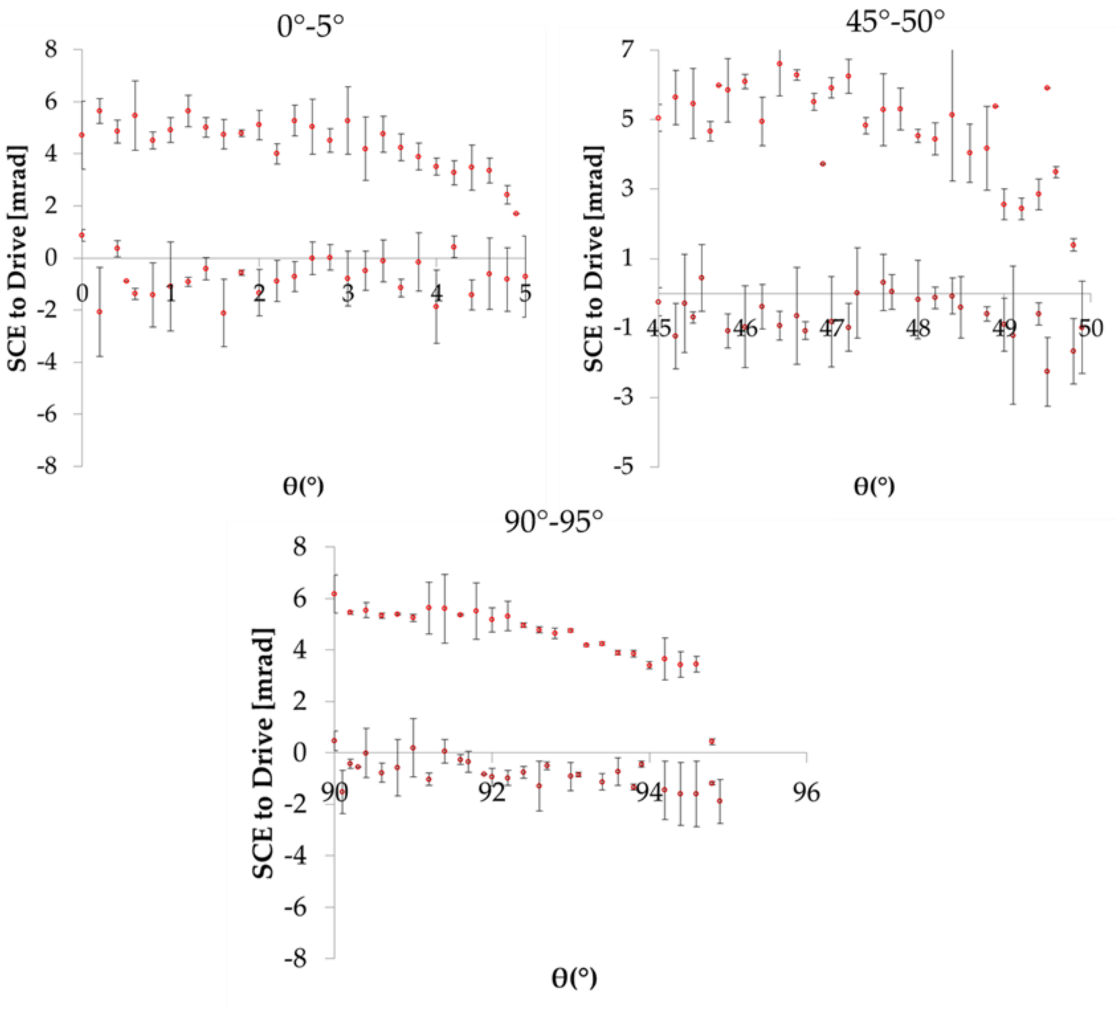

Figure 7. Measured relative twist of SCEs (1 and 6) of the EuroTrough Prototype at PSA with a single inclinometers system per SCE for 0º-5º, 45º-50º and 90-95º angle ranges.

4.3 Equipment

The equipment depends somehow on the objective. Table 5 details some equipment that may be used for measuring torsional stiffness of parabolic-trough collectors.

Table 5. **Equipment for the measurement of torsion stiffness of parabolic-trough collectors**.

Item	**Description**	**Example**
Inclinometers	Instruments for measuring angles of surface movements and deformations	• Single inclinometers per SCE system :Sensorex_sx41100 • multy inclinometers per SCE system :Zerotronic Typ C from WYLER
Mounting adapters	Aluminium profiles with magnets for relative measurements Profiles placed on reference drillings for absolute measurements	
Force Meter	Measure forces with an accuracy of 1N to Forces up to 2000 N	Kern HCB200k100
Auxiliary equipment	Cables, laptop, tape, securing strap	

Figure 8. Right hand-WYLER Inclinometer mounted to the end-plate of a parabolic trough with a magnetic adapter. Left-hand Sensorex_sx41100 inclinometer mounted on the torque box of a parabolic trough.

4.4 Sensor Calibration

Inclinometers are rather delicate devices and handling at ambient conditions may significantly affect the measurement accuracy. The handling instructions and measurement accuracy may be taken from the data-sheet of the respective manufacturer. In any case, it is strongly recommended to cross-check the measurement accuracy on a regularly basis with an absolute reference. Such references are absolute rotary encoders. CIEMAT has set up such a test-bench as depicted in Figure 10.. Comparison between the results from the absolute rotary encoders and the inclinometer data may reveal any non-linearity of the inclinometer.

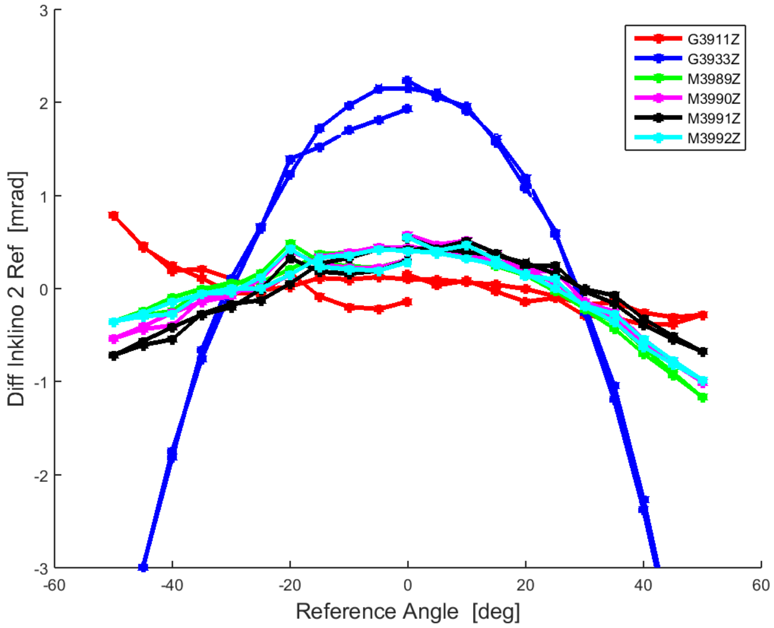

Figure 9. Results from Sensor calibration with the absolute encoder test bench. 5 out of 6 inclinometers show moderate deviation from the linear behaviour with only small deviations of 1 mrad/45°. However, the inclinometer with ID G3933Z shows a distinct characteristic and can thus not be used for high precision CSP applications without recalibration by the vendor.

Figure 10. CIEMAT's test bench for inclinometer calibration. Right hand Zerotronic Typ C from WYLER inclinometers and left hand Sensorex_sx41100 inclinometers being calibrated.

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