

Analysis of Alignment Data for Auger Fluorescence Telescopes

by

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1 Introduction

The Pierre-Auger-Observatory, designed to detect ultra-high-energy cosmic rays (UHECR), is located in Argentina at an altitude of 1400 m close to Malargüe. UHECR are classified as particles with a kinetic energy greater than 10^{18} eV. It is interesting to investigate these particles because there isn't any research-technology developed, which is able to accelerate particles to this energy level in a controlled way. And even if that would be possible, it is not yet possible to steer the particles. The reason for the latter is that high energy particles are less deviated from magnetic fields than low energy particles, which makes it hard to keep the high energy ones on a stable track. Consequently the Pierre-Auger-Observatory measures the products of the interaction between these particles from space and the earth's atmosphere.

Cosmic rays have energies from 10^6 eV to 10^{20} eV. Above 10 GeV the cosmic ray flux, which is defined as

$$\Phi(E) = \frac{d^4N}{dEdAd\Omega dt}, \quad (1)$$

approximately follows the following power law distribution (which can be seen in figure 1):

$$\Phi(E) \propto E^{-\gamma}. \quad (2)$$

In equation (2) γ depends on the energy of the cosmic rays in the following way:

- $\gamma = 2.7$ for $E < 4 \cdot 10^{15}$ eV.
- $\gamma = 3$ for $4 \cdot 10^{15}$ eV $< E < 5 \cdot 10^{18}$ eV.
- $\gamma < 3$ for $E > 5 \cdot 10^{18}$ eV.
- $\gamma \gg 3$ for $E > 10 \cdot 10^{20}$ eV.

For detailed information regarding cosmic rays and their origins see [1].

Designed in a hybrid way the Pierre-Auger-Observatory has two types of detectors.

The first part is called "Surface Detector" (SD). It is a ground detection system made of water Cherenkov detectors, which are very good at detecting muons and electrons/positrons. These particles are frequent products of the interaction between UHECRs and the atmosphere. Figure 1 shows that the cosmic ray flux is extremely low at high energies, which is why a large amount of SDs has to be installed over a big area. Altogether 1600 water Cherenkov detectors cover an area of 3000 km^2 to compensate the low particle flux at high energies and to get an effective measurement.

The second detector system is called "Flourescence Detector" (FD). They consist of 24 regular telescopes distributed in four buildings¹ with six telescopes² each and three "High Elevation Auger Telescopes" (HEAT) which are both able to detect ultraviolet flourescence light. This light is also a product of the aforementioned interaction, which is mainly electromagnetic interaction. The regular telescopes and the HEATs are almost identically constructed. The difference between

¹The buildings are located at Los Leones, Los Morados, Loma Amarilla and Coihueco.

²These stacks of telescopes are sometimes referred to as "eyes".

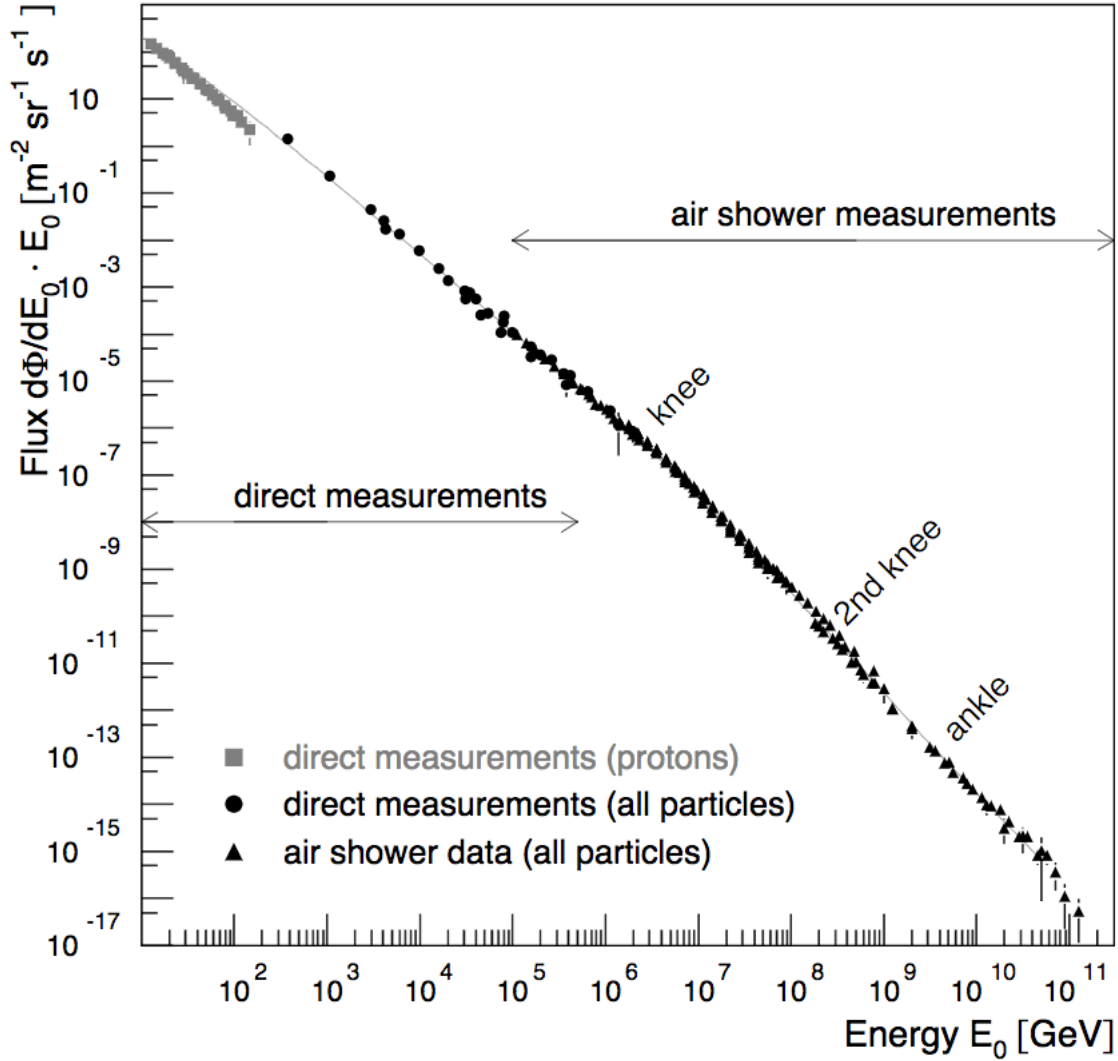


Figure 1: Ultra-high-energy particle spectrum. At low energies only protons were taken into account for this plot and at high energies all particles were used for the measurement [2].

the regular telescopes and the HEAT enhancement, which was constructed in 2009, is that the HEATs are able to be tilted 30 degrees towards the sky. Since all the telescopes have a field of view of 30 degrees, this means that the HEAT telescopes can, additionally to the regular 0 to 30 degrees, measure light between 30 and 60 degrees. While the regular telescopes lower measuring limit is 10^{18} eV the HEAT enhancement allows measurements down to 10^{17} eV [3]. Note that the HEATs can only be tilted the full 30 degrees ("upward mode") or operate on ground level ("downward mode").

The observatory's SD and FD hybridization allows a cross-calibration and therefore significantly reduces systematic uncertainties. This detecting mechanism results in a very accurate event reconstruction.

This bachelorthesis has two objectives:

1. Deliver a description of the ways to get the tilt monitoring data from the telescopes.

2. Examine the accuracy of the HEAT tilting sensors by looking at the correlation between the sensors themselves and between the weather and the sensors.

The former should ensure that future physicists have an easy way to learn how to access the data. This thesis divides the first objective into three parts. Firstly it describes the general workings of the fluorescence detectors. Secondly it deals with the tilt monitoring system of the HEATs and then it shows how to download and view the tilt monitoring data. The latter objective should ideally substantiate the high accuracy of the observatory, or in the worst case show shortcomings of the HEATs. The analysis will look at how the shifting process affects the data. Moreover it will examine the effects of three different aspects of the weather - temperature, wind and earthquakes - onto the tilt data.

2 High Elevation Auger Telescopes

Before the ways to get the data from the tilt sensors are described, a general description of the telescope's setup is given in order to understand the data.

2.1 General Structure of the Fluorescence Detectors

As mentioned above the interaction of the UHECR particles with the nitrogen atoms in the atmosphere results in the emission of ultraviolet fluorescence light. Since this light is emitted isotropically it can be detected at ground level using telescopes and the shower core as well as the direction of the incoming particles can be reconstructed.

Since the 24 regular telescopes and the three HEATs are structurally identical the schematic representation shown in figure 2 qualifies for both types. It shows the different components of the telescope.

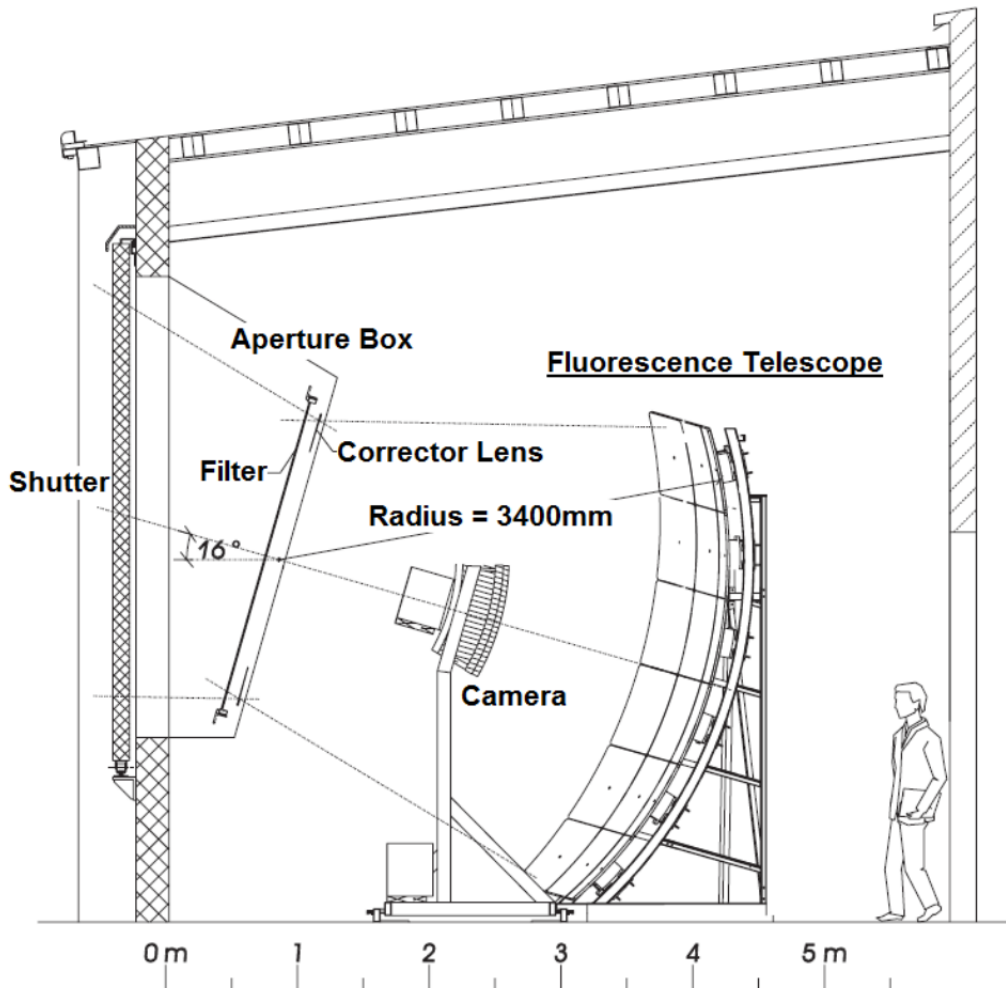


Figure 2: Scaled schematic setup of the fluorescence detector[3].

The telescope consists of the following components. The telescopes have an aperture of 2.2 m, which also functions as an optical filter transparent to UV light to reduce the visible amount

of ambient background light. Shutter doors are installed in front of the windows in order to protect the interior from weather and too much light. Thus these doors are closed during the day. There is a $3.5 \text{ m} \times 3.5 \text{ m}$ spherical mirror with a radius of 3.4 m inside the telescope, which in the HEATs is made out of aluminum coated glass. Light incoming through the window is reflected by the mirror onto a camera made up of 440 pixels arranged in a 22×20 matrix. Each of these pixels is a photomultiplier (PMT) with a hexagonal front and a field of view of $1.5^\circ \times 1.5^\circ$. The optical axis, which traverses the centers of both camera and mirror, forms an angle of 16° with the horizontal axis. The interior of the telescopes can be seen in figure 3.

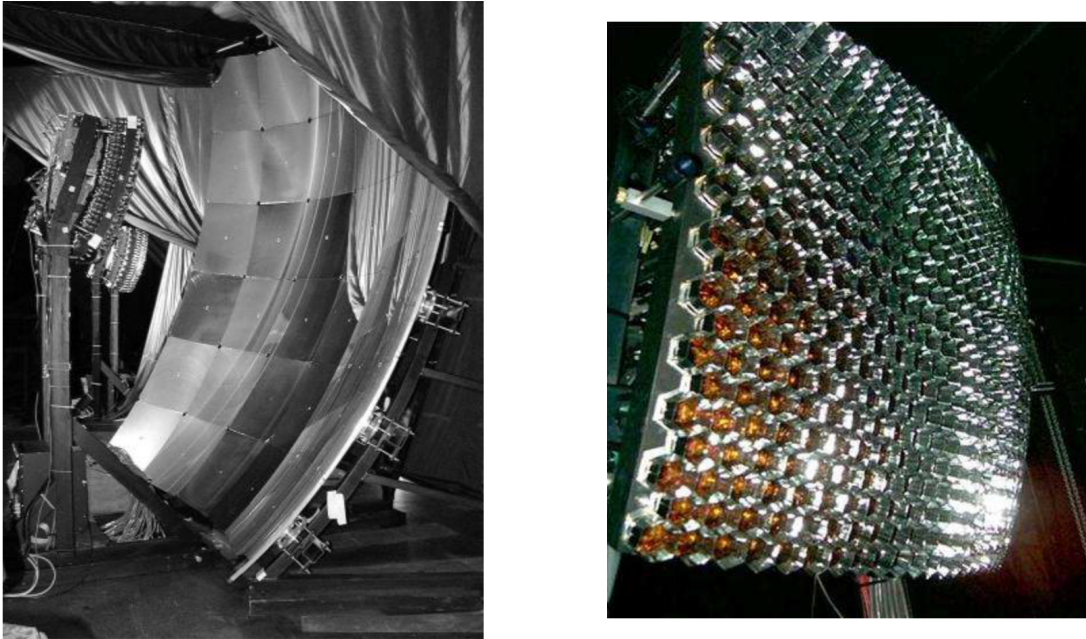


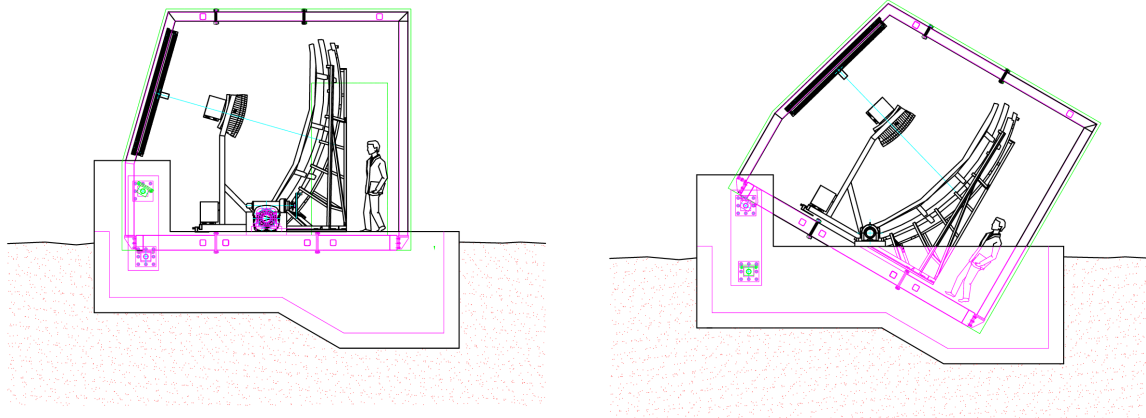
Figure 3: Both pictures show the interior of the camera. Left: Photo of a camera and a mirror. Right: Close up of a camera [4].

The High Elevation Auger Telescopes are located 180m north-east of the Coihueco FD station. As mentioned above the three HEATs can be tilted. They have two modes called "upward" and "downward" whereas the former means that the telescopes are tilted upward 30° . Both modes schematics are displayed in figure 4.

The "downward" mode can be used to calibrate the HEATs by comparing their data to the regular FDs. When the HEATs are in "upward" mode they can be combined with the telescopes of the close station "Coihueco" to form one virtual FD eye called "HECO" which is able to measure shower profiles with extra high accuracy.

2.2 Tilt Monitoring System for HEAT

In order to monitor the optical stability of the HEATs interior the so called "Tilt Monitor" system was implemented. The system consists of eight simple but accurate sensors which measure the position of the components relative to each other. There are two types of sensors build into the telescopes. The first type are inclination sensors and the second type distance sensors. Four of



(a) Schematic representation of the "downward" mode. (b) Schematic representation of the "upward" mode.

Figure 4: HEAT detector schemes for the ways the telescopes can be tilted [5].

each sensors are build into each of the HEATs. This sensor system was developed and tested in depth by J. Calvo de No in his diploma thesis [3].

Figure 5 shows the schematics of the positioning of the sensors.

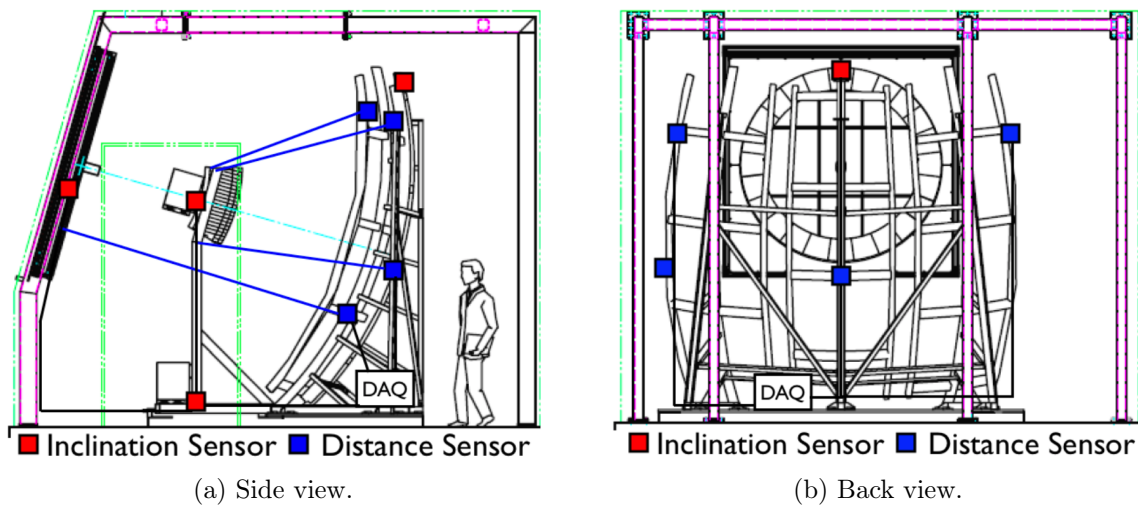


Figure 5: Schematics of the sensor positioning [1].

The following description of the location of the sensors is made from the point of view of someone standing behind the mirror and looking in the direction of the shutter³. The inclination sensors are at the following positions:

1. at the base of the camera,
2. at the top of the camera,
3. at the top middle of the mirror and
4. at the left side of the shutter.

³Just like the person in figure 5a. He would see the back view in 5b.



Figure 6: Photo of the HEATs tilted in "upward" mode [4].

The distance sensors measure from the⁴:

1. top left of the mirror to the top left of the camera,
2. top right of the mirror to the top right of the camera,
3. bottom left of the mirror to the shutter and
4. center of the shutter to a point beneath the camera.

These sensors can provide for example information about the relative distance between camera and mirror and/or the relative inclination between the two. This can be used to ensure a stable event reconstruction which would not be possible, if the actual positions differ from the expected ones.

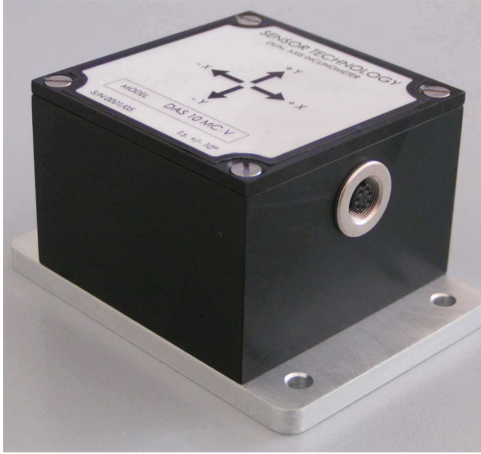
The following paragraphs provide further description of the sensor. If you want a highly detailed description of the sensors and of their calibration see [1], [3] and [6].

2.2.1 Inclination Sensors

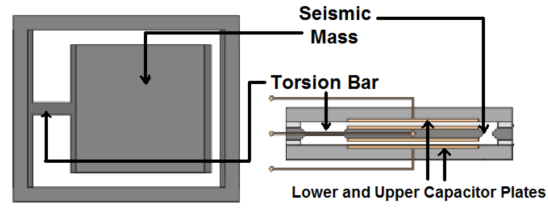
Since the HEATs are tiltable by 30° the design goal for the inclination sensors was to have a minimum measurement range of 30° with a minimum accuracy of $\Delta\alpha \approx 0.1^\circ$. So the chosen inclination sensors are four bi-axial capacitive MEMS⁵ sensors, working on a silicon capacitive transducer basis. The exact name of the Dual Axis Inclinometer is "DAS-15-MC-RS232". It and it's schematic working mechanism can be seen in figure 7.

⁴The first mentioned position is the actual location of the sensors.

⁵Micro Electro-Mechanical System



(a) Inclinometer Sensor DAS-15-MC-RS232 [3].



(b) Working principle of the capacitive inclination sensor [7].

Figure 7: Photo and schematics of the inclination sensor.

The resolution of the sensors is approximately $0.01^\circ \equiv 1$ bit. The official measurement range of the sensors is $\pm 15^\circ$ which alone would be barely sufficient for the design goal because the sensors are installed with a 15° preset. In addition to that J. Calvo de No found out during the calibration that the sensors are accurate within a range of $\pm 20^\circ$. The tests also showed that, against the manufacturers classifications, the sensors are sensitive to temperature. This thesis should reveal later whether this is a problem or not. The inclinometers signal is already digitized and connected via a RS232-to-USB hub to the computer. Since these sensors are bi-axial it is also useful to know, that the X-axis of the sensor is the axis in which the telescopes are being intentionally tilted. This means that mainly the X sensors inclination data will be examined. Later it can also be seen that the sensors are all calibrated differently. That means, that for all X-axis sensor values the lower one means "upward" mode and the higher one, ideally⁶ 30° higher, means "downward" mode.

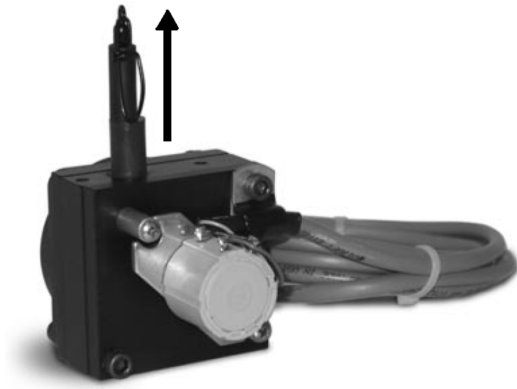
2.2.2 Distance Sensors

The design goal for the distance sensor was to have a minimum accuracy of 0.5 mm. The distance sensors chosen are potentiometers called "PTX-101" by the company Celesco, since they have a theoretically infinite resolution⁷. They can be seen in figure 8.

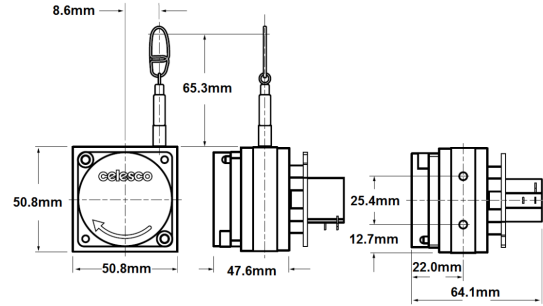
During the calibration J. Calvo de No found the resolution of the sensors to be 0.1 mm. This translates to a calibration of $0.88 \frac{V}{cm}$. As can be seen later the relative resolution is actually much higher. Unlike the inclination sensors, which digitize their output signal automatically, the distance sensor provide an analog voltage signal. The output voltage is linear with the extension of the cable. This signal is converted with an analog-to-digital-converter (ADC) (μ -Box) and fed into LabVIEW. Since the distance sensors have a maximal elongation distance of 5 cm temperature stable cables are attached to the sensor and onto the points mentioned above. Note that the cable of the distance sensor is pulled back by a string with a force of 15 N.

⁶I write ideally, because it can later be seen that the values do not allways differ exact 30° , but they are very close.

⁷This statement seemed exagarated for me. But you can see it in [3] on page 31.



(a) Distance Sensor PTX-101 [3].



(b) Working principle of the distance potentiometer [8].

Figure 8: Photo and schematics of the distance sensor.

2.2.3 Data Acquisition

Figure 9 shows a schematic representation of the data acquisition (DAQ) process. Beneath the mirror there is a computer which reads out the input from the inclination sensors as well as the μ -Box output. The latter is also connected to the computer via USB. The computer constantly runs a LabVIEW DAQ software which can be used to control the settings of the measurement process. The output of the sensors is written into the Auger monitoring MySQL database, which is also done via a LabVIEW program. It can be accessed via a remote desktop connection. From the time period of 2009 to the beginning of 2016 the sensors have been read out with a frequency of 1 Hz. Since then only one datapoint per minute has been written into the database. While all data of the inclination sensors is measured in regular degrees [$^{\circ}$], the distance sensors data is measured in centimeter. The numeration from the positions of the sensors in the section "Tilt Monitoring System for HEAT" is the same as the numeration in the database.

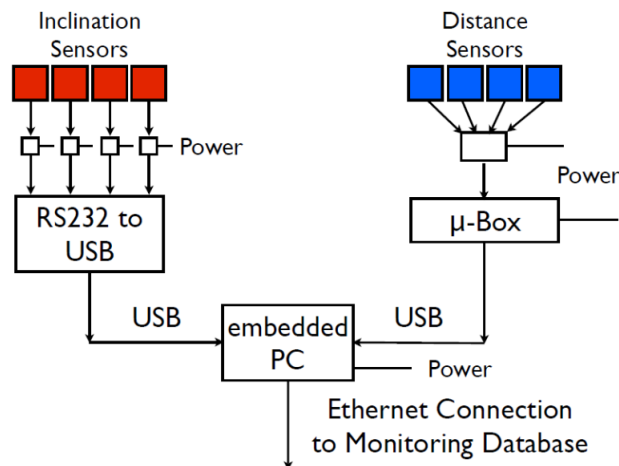


Figure 9: Schematic of the data acquisition process [3].

3 Accessing the Data

All the data from the telescopes is written in the Auger monitoring MySQL database. A handy way of viewing this data through your browser is using a PhpMyAdmin page. In the following paragraphs the usage will be explained. There will also be shown how to access the data using Python.

The data that has been worked with for this bachelor thesis is stored on the RWTH-cluster at the hpcwork/phys3aauger directory. There is a folder "tiltmonitoringNew" which contains all tilt data sorted by year.

3.1 Viewing the MySQL Database in the Browser

First of all there are two username and password combinations that you may obtain from Professor Hebbeker. In order to be able to refer to them later they are hinted below. The access datasets are:


1. Username: R***** - Password: *****
2. Username: b***** - Password: *****

The university in Wuppertal set up a mirror to access the PhpMyAdmin page easily. You can get to the mirror via this link mon.auger.uni-wuppertal.de. To access the page you will need the second access data. On the mirror you can also enter the Auger Monitoring Wiki which, amongst other things, explains how to use the MySQL database.

From there click on PhpMyAdmin to get to the page to view the MySQL database through the browser. Enter the first username and password combination to access the database. Both pages can be seen in figure 10.

Auger Monitoring (pro version)
Auger Monitoring (daily snapshot)
Auger Monitoring Wiki
Auger UpTime root-files
FDMon Wiki
JPGraph Manual
PHP-MyAdmin
Contact

(a) Wuppertal mirror.



(b) PhpMyAdmin.

Figure 10: Screenshot of the login pages.

In order to understand the page you want to understand the basic structure of MySQL databases. A server⁸ can have multiple databases and a database can have several tables.

⁸In case of the Auger data the server host is: paomondb.physik.uni-wuppertal.de.

So once you are logged in on the PhpMyAdmin page there are several databases to choose from. All of the Auger data is stored here. This bachelor thesis mainly uses the database "FDHeat" since all the tilt monitoring data is captured there. The table "Weather" from the "AugerMonitor" database is also relevant. The weather data in that table captured by the station "Coihueco" will be used later, because it is the closest weather station to the HEATs. The two most important tables of "FDHeat" for this bachelor thesis are "HeatDistTab" and "HeatIncTab" since they contain the output of the tilt sensors.



Figure 11: Menu for a table.

If one table is chosen by clicking on it you can see the menu bar in figure 11 at the top of your browser window. Helpful buttons of this menubar are browse, structure and search. Since all the inserting of data is done automatically by the LabVIEW program mentioned in section 2.2.3 and the exporting of the data is done later in Python the other buttons aren't relevant for this thesis. The "structure" button shows you which datasets are in the table.

The "browser" button shows you the recorded data points for all the fields⁹. You can navigate through the data by clicking through the pages.

The "search" button shows you a GUI for queries. You can enter limitations in the fields and click on "go" which will browse the chosen table with those limitations. Note that the used query can then be seen under the field "SQL query". This is an easy way to get the desired MySQL syntax for Python.

3.2 Logbooks

There is a variety of logbooks used to document the working steps done by the Auger crew in Argentina. You can access the general page¹⁰ for all the logbooks via this link <http://www.auger.org.ar/Elog/>. You might need to enter the second username and password combination to access this and the following websites.

The link "Flourescence Detector"¹¹ takes you to the e-log of the time period before November 2007. Unfortunately there is no HEAT data recorded before 2007 since it was build in 2009. But on the top of this page there is a link called "Old style e-log"¹² which gives you access to HEAT data from 2009 to April 2011. The bottom link "New e-log format, after Nov 2007" is defect as of this writing.

Also on the general page below "The Hybrid Detector" there is a link "FD local page"¹³ which

⁹It will use the default query, which is just show 30 entries at a time.

¹⁰Note that there is a help page link displayed immediately if you access the general page http://www.auger.org.ar/Elog/auger_elog_hints.html.

¹¹<http://wiki.auger.org.ar/doku.php?id=fd:elog>

¹²<http://www.auger.org.ar/cgi-bin/Elog/det-system-elog.pl?nb=fd&action=view&page=last&scroll=true>

¹³<http://www.auger.org.ar/FD/>

takes you to the FD page. On this page you can access the shift log¹⁴ and the task log¹⁵. With all these logbook variants one is able to interpret the tilt data. If the data happens to have periods in which there is no data recorded the explanations (e.g. maintenance) might be found in the logbooks. If a log book has been used in the analysis, it will be mentioned which logbook has been used when.

3.3 Python

To work with a MySQL database in Python one needs to install and import a Python module such as "MySQLdb". In order to go over the basic commands to access the database via Python, figure 12 shows a short example program¹⁶ to export the distance data for the past six months.

```
1 import MySQLdb as mdb
2 #from datetime import datetime
3
4 interval = '6 MONTH'
5
6 connection = mdb.connect('paomondb.physik.uni-wuppertal.de', 'R',
7                          'FDHeat');
8
9 cursor = connection.cursor()
10 cursor.execute("SELECT VERSION()")
11
12 version = cursor.fetchone()
13 print "Database version : %s " % version
14
15 file = open('../Daten/heatDist_test_new.dat','w+')
16
17 cursor.execute("SELECT * FROM HeatDistTab WHERE TIME >= NOW() - INTERVAL %s" %
18               interval)
19
20 rows = cursor.fetchall()
21
22 for row in rows:
23     file.write(str(row) + '\n')
24
25 file.close()
26
27 connection.close()
```

Figure 12: Easy python program example showing how to download the HEAT distance data from the MySQL database.

The first important line is the one defining the connection. Similar to the way it is done in the browser the Python command takes a hostname, a username, a password and a database.

The second important thing is the cursor. The cursor defines which parts of the database you want to access. If you call the execute function you can have the cursor execute the MySQL syntax commands. As it can be seen in line 22 the MySQL query syntax looks a little bit like the import syntax from python. You choose which datasets you want to export from which table and you can give limitations. The fetch command fetches all (or in case of line 11 just one) row(s) of a query result and returns a list of tuples. The rest of the program writes this list into a file.

If you want to view and use the Python programs I used to process the data they are also on the

¹⁴http://www.auger.org.ar/FD/fd_shift_log/

¹⁵http://www.auger.org.ar/FD/fd_task_log/task-main.php

¹⁶All code written by me.

hpcwork/phys3aauger directory in a folder called "JanHesters". Make sure to receive the rights to access the hpcwork/phys3aauger cluster, otherwise you are not able to access the directory. There you can find the programs to plot the data. You may also use the ".npy" files in which I saved the data as arrays for a faster data processing. These ".npy" are special numpy files, which can be loaded very quickly by the numpy directory. In the ".npy" files is the data of each year saved in a numpy array.

4 Analysis of the Tilt Monitoring Data

In the following analysis the tilt data will be examined. At first it will be examined which fluctuations are normal for the sensors. Then secondly it will be checked whether there are correlations between two axis of the inclination sensors of one bay. Furthermore the repercussions of the shifting process onto the data will be evaluated as well as the effects of the weather in the form of temperature, wind and earthquakes.

For the analysis the data of each year has been downloaded from the MySQL database and saved on the RWTH cluster. In order to get a basic overview of the data each year of each HEAT bay was plotted. Since printing all 18 plots would be too much only the year 2011 of bay 2 is displayed below in figures 13 and 14 as an example, as it is one of the most complete data sets. That means that year has not many empty spaces in the plot, which arise if the telescope is maintained or if the telescope has a malfunction. Because of the great amount of datapoints only every 100th datapoint is being displayed. The temperature in the plot is the temperature measured at the weatherstation in Coihueco.

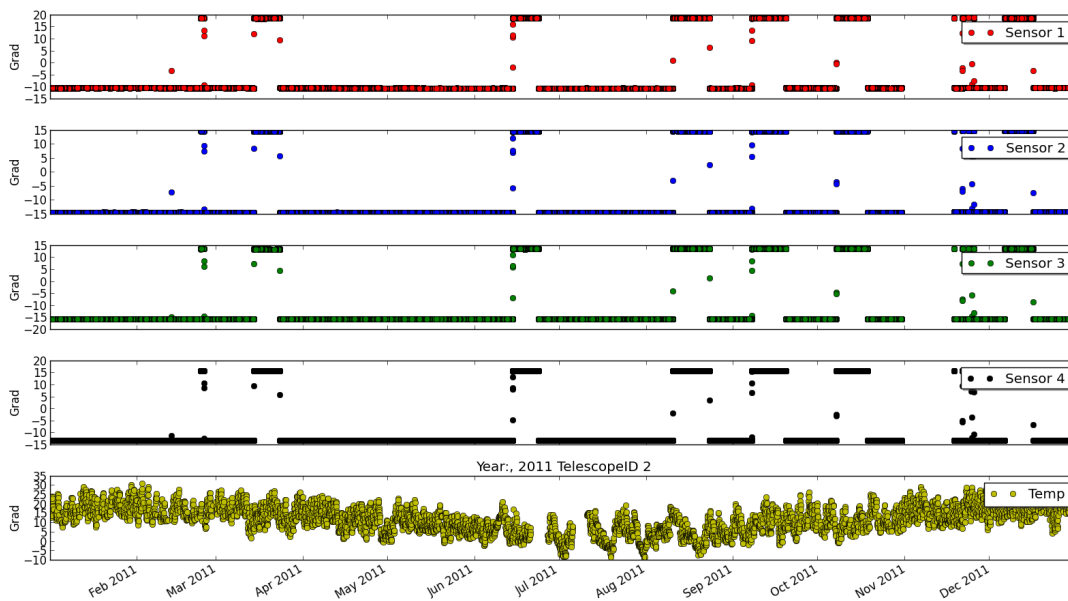


Figure 13: Inclination data of bay 2 in the year 2011. The first four subplots show the shift angle in degree, the last subplot shows the temperature.

4.1 Normal Variations

In order to see which fluctuations are unusual in the data a regular timeinterval will be examined first. As can be seen in figure 13 above in 2011 there was a clean measurement period in "upward" mode for bay 2 during April. Therefore this period will be used to determine the fluctuations of the sensors. Since there might be different variations for each bay, the same analysis will be made for a time interval with complete datasets for bay 1 and 3. After looking at the data of all the years, the month of September 2014 was chosen for bay 1 and May 2014 for bay 3. You

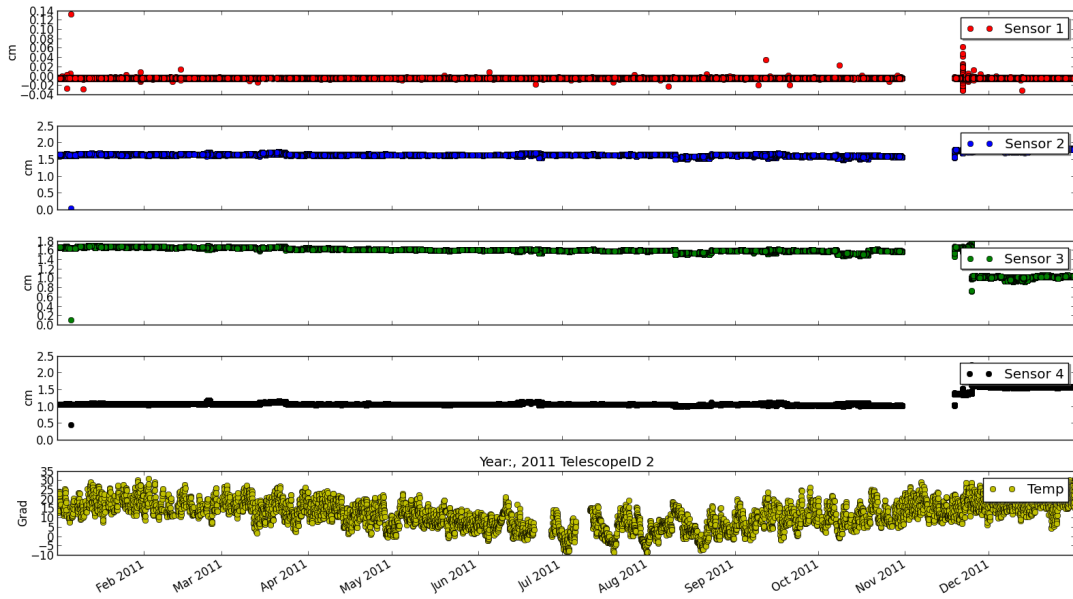


Figure 14: Distance data of bay 2 in the year 2011. The first four subplots show the distance sensor values in centimeter, the last subplot again shows the temperature.

can see all three plots years in figures 15, 16 and 17. Note that you can see the binning of the inclination sensors data in bay 1's plot.

For these months the means and variations displayed in tables 1, 2 and 3 have been determined.

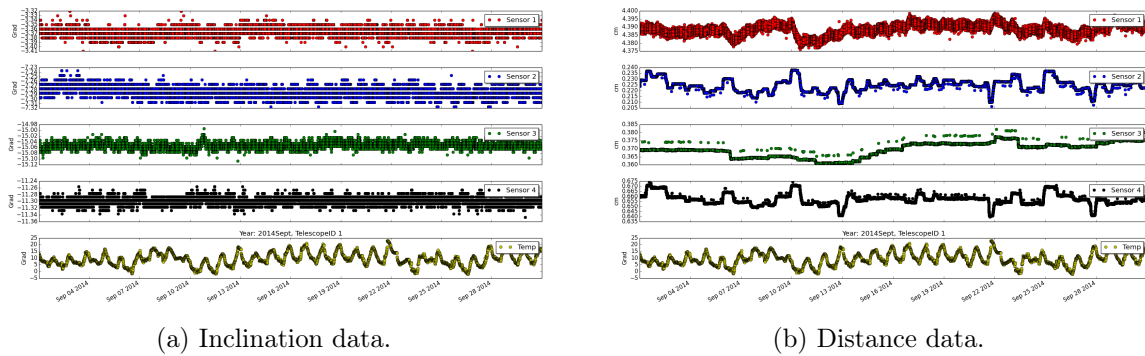
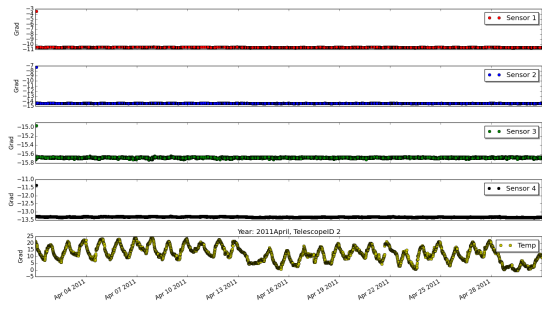


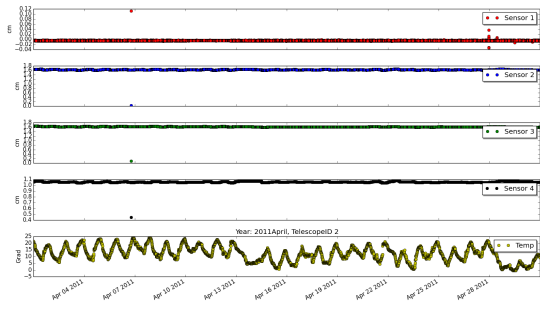
Figure 15: Bay: 1; Year: 2014, Month: September.

ID1	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	4.389	-3.367	0.225	-7.283	0.370	-15.052	0.657	-11.299
Var	0.003	0.008	0.005	0.010	0.004	0.010	0.005	0.009

Table 1: Bay: 1; Year: 2014; Month: September; Means and variances of the distance and inclination values throughout the whole month.

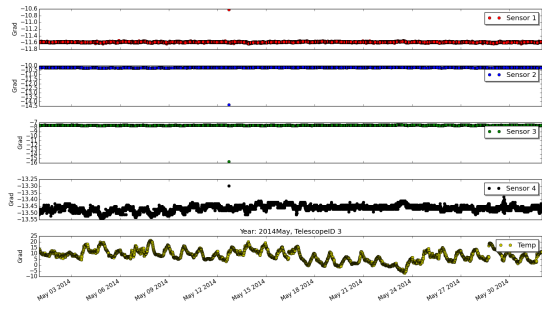


(a) Inclinometer data.

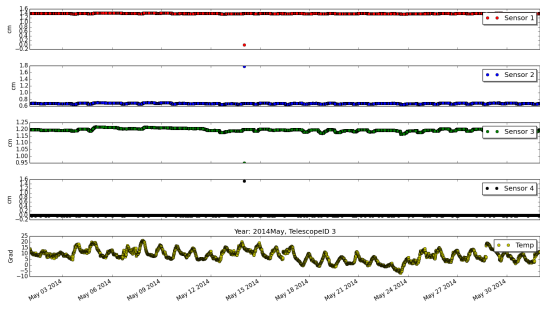


(b) Distance data.

Figure 16: Bay: 2; Year: 2011, Month: April.



(a) Inclinometer data.



(b) Distance data.

Figure 17: Bay: 3; Year: 2014, Month: May.

ID2	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	-0.005	-10.59	1.628	-14.426	1.617	-15.677	1.057	-13.316
Var	0.001	0.027	0.013	0.017	0.011	0.011	0.008	0.016

Table 2: Bay: 2; Year: 2011; Month: April; Means and variances.

ID3	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	1.399	-11.582	0.681	-10.197	1.197	-7.584	-0.002	-13.464
Var	0.010	0.010	0.012	0.019	0.010	0.042	0.001	0.020

Table 3: Bay 3; Year 2014; Month May; Means and variances

Since all the sensors frequently get recalibrated during periods of maintenance the means are only included for completeness. They may change over time. The variances are of greater interest. As you can see the variances of the inclination sensors are stable and consistently very small. The variances of the distance sensors however display a little bit stronger fluctuations due to different binning. Both types of variances are well below the desired reference value of the telescopes' design.

4.2 Correlation Between the X- and Y-Axis

There is one axis, that hasn't been considered yet, which is the y-axis of the sensors. The y-sensors describe the change of the angle horizontally. As it turns out the months examined above are also stable concerning their respective y-axis values and therefore they also work well for a correlation analysis. The plots for the y-axis values are in figures 21, 22 and 23 in the appendix.

To see whether the sensors correlate with each other the correlation coefficients are in table 4. The same months are used as above.

ID / Corrcoef	X1 / Y1	X2 / Y2	X3 / Y3	X4 / Y4
Bay 1	-0.078	0.272	-0.059	0.242
Bay 2	0.077	-0.200	0.109	-0.689
Bay 3	-0.044	-0.702	0.234	0.487

Table 4: Correlation coefficients of the X inclination axis to the Y inclination axis.

As can be clearly seen there is almost no correlation between the axis of the inclination sensors. Even though the X2 / Y2 correlation of bay 3 and the X4 / Y4 correlation of bay 2 are a little bit higher and stand out, it is very likely that this is just the case because of chance. There are two reasons for this assumption. On the one hand the HEATs are identically constructed and since the respective correlation coefficients in two out of three bays are low they shouldn't be high in the other bay. And on the other hand, if one of the sensors shows a high X-Y-correlation, all the other sensors in the same bay should display the same behaviour, because they experience the same tilt. But as can be seen above the other sensors of bay 2 and 3 have low correlation coefficients.

4.3 Shift Stability

To check how the shifting of the telescope affects the data two shift positions, one upward and one downward, of each telescope will be examined. To get similar conditions for the shifting process for each bay the inclination data of all years have been examined searching for a time period where all telescopes were shifted simultaneously. This was the case in June 2011¹⁷. In the appendix in figure 24 you can see a close-up of the shift from "upward" into "downward" and vice versa. Displayed below in tables 5 and 6 are the means and variances from bay 1 as an example. The values for bay 2 and 3 are in the appendix in tables 13, 14, 15 and 16. For some reason which is not

¹⁷If you visit the shift-log via this link http://www.auger.org.ar/FD/fd_shift_log/ and click on "browse entries" you can see that the shift period ended on the 9th of June. The HEATs were tilted upwards again on the 22nd of June.

mentioned in the logbooks there was no distance data recorded for bay 1 during the shifting period.

Bay ID1	IncX 1 [°]	IncX 2 [°]	IncX 3 [°]	IncX 4 [°]
Mean	-3.457	-7.304	-14.972	-11.365
Variance	0.009	0.009	0.006	0.008

Table 5: Bay: 1; Pre-shift. Means and variances of the three days immediately prior to the shift. This implies that the telescope was completely in "upward" mode.

Bay ID1	IncX 1 [°]	IncX 2 [°]	IncX 3 [°]	IncX 4 [°]
Mean	25.36	22.475	14.195	17.923
Variance	0.012	0.012	0.006	0.008

Table 6: Bay: 1; Post-shift. Means and variances of the three days immediately after the shift. This implies that the telescope was completely in "downward" mode.

Comparing the standard deviations before and after the shift leads to the conclusion, that there are no noteworthy changes. You can only see the calibration error of the inclination sensor 1 in bay 3. A miscalibration caused the mean value to be unusually high. This problem started in December 2010 and has been fixed in September 2012¹⁸. Other than that the sensors seem to be stable. The values collected in this shifting periods also match the values of the measured normal fluctuations. Note that the inclination means don't add up to a thirty in each degree shift. The distances between the shifts in degrees can be found in table 7. They are calculated by adding up the absolute values of the corresponding pre and post shift values of each bay. The means for the shift distances of each bay are also calculated. Due to its miscalibration sensors 1 of bay 3 is not considered in the calculation.

Bay	Inc 1 [°]	Inc 2 [°]	Inc 3 [°]	Inc 4 [°]	Mean \pm variance in [°]
ID 1	28.817	29.799	29.167	29.288	29.268 \pm 0.352
ID 2	29.024	28.946	29.059	28.924	28.988 \pm 0.055
ID 3	1.124,793	28.919	29.245	29.055	29.073 \pm 0.134

Table 7: Shift distances: the difference between the X inclination values of the telescope in upward and downward mode.

The calculated means aren't close to 30°. This along the fact that the sensors are super accurate makes it unlikely, that they are not well enough calibrated and that the HEAT don't shift perfect 30°. They actually tilt closer to 29°.

4.4 Weather Correlation

There are weather aspects that might affect the sensors. In the following the effects of the outside temperature, the wind and earthquakes on the sensors are examined. The same clean months as

¹⁸This is not described in the logbook. You can only see it in the plots of the inclination data that September 2012 was the last time where the data for that sensor reached these unusually high values.

in the evaluation of the general fluctuation will be used.

4.4.1 Temperature

In order to calculate the correlation coefficients between the temperature and the sensor data both datasets need to have the same size. But there is only one value recorded for the temperature every 10 minutes, whereas the distance and inclination data has been recorded with a frequency of 1 Hertz. To be precise the temperature is measured every fifth, 15th, 25th etc. minute (e.g. 00:05, 00:15, 00:25 ...). In order to compensate for this the distance data in the intervals around the measuring points of the temperature (e.g. 00:00 - 00:10, 00:10-00:20, ...) have been summarized into one point and these points have been written into a new array. For this array the correlation coefficients are displayed in table 8 and 9 below. There are also plots showing the values with their error in figure 25 in the appendix. The error is obtained by calculating the statistical error between the summarized points. Note that in order to be able to see the error bars only every 10th value has been plotted in this figure. And even then the errors of the distance data are so small that you can barely see them, which means that the datasets were very stable.

ID / Corrcoef	Dist1 / Temp	Dist2 / Temp	Dist3 / Temp	Dist4 / Temp
Bay 1	0.4895	-0.4076	0.2203	-0.4434
Bay 2	-0.0858	-0.0442	0.0378	-0.3316
Bay 3	-0.0148	-0.0282	-0.0093	0.002

Table 8: Correlation coefficients between distance data and temperature.

ID / Corrcoef	X1 / Temp	X2 / Temp	X3 / Temp	X4 / Temp
Bay 1	0.0955	-0.3253	-0.0037	-0.2871
Bay 2	0.2663	0.2662	0.2617	0.2657
Bay 3	-0.0878	0.2982	0.1785	0.0214

Table 9: Correlation coefficients between X inclination data and temperature.

As you can see in tables 8 and 9 the correlation between the sensors is generally low. The values for the correlation coefficient between the distance data and the temperature is between 0.5 and 0. Those who are close to 0 obviously show that there isn't any correlation. This is especially true for bay 3. Bay 1's sensors seem to be a little more sensitive to the temperature. The inclinatinon sensors on the other hand fluctuate between approximately 0.3 and 0. So they are a little less dependant on the temperature. It makes sense that the distance sensors show a stronger dependence than the inclination sensors, since there are wires involved in the measuring process.

4.4.2 Wind

In order to check the correlation between the wind and the data of the telescopes, the same algorithm which has been used with the temperature is used. This means that again the tilt data will be summarized so that it can be used to compute a correlation coefficient.

First it is useful to know how strong the wind gets at Coihueco, because strong winds are obviously

more likely to move the heavy telescopes than weak winds. The weatherstation collects three types of data for the wind:

1. Current Windspeed,
2. Average windspeed (over the interval of 10 minutes) and
3. Maximum windspeed (in the interval).

In order to know when strong wind was, the maximum average windspeed has been exported for every year:

Year	2009	2010	2011	2012	2013	2014	2015	2016
Windspeed [km/h]	93.1	107.4	107.61	80.09	64.33	117.82	64.91	96.34

Table 10: Maximum average windspeeds of every year.

As mentioned above the years 2011 and 2014 have a high data density. Table 10 shows that these are the years with the highest average windspeeds. Therefore the correlation coefficient will be calculated for the months in which these windspeeds have been measured. The months are June in 2014 and May in 2011 and coincidentally all three bays have been continuously in "upward" mode during these months. In tables 11 and 12 the values for the correlation coefficients between the sensors of the bays can be found.

ID/Corrcoeff	Dist 1	IncX 1	Dist 2	IncX 2	Dist 3	IncX 3	Dist 4	IncX 4
1	-0.128	0.0314	-0.0867	0.0237	0.0531	0.0723	-0.2095	-0.1253
2	0.013	-0.0221	0.0054	-0.0434	0.0012	-0.0189	0.0079	-0.0037
3	0.0452	-0.0159	0.0092	-0.0174	0.0328	-0.0327	0.0447	0.0694

Table 11: Correlation between average windspeeds and tilt data for May 2011.

ID/Corrcoeff	Dist 1	IncX 1	Dist 2	IncX 2	Dist 3	IncX 3	Dist 4	IncX 4
1	0.2571	0.039	0.203	-0.0738	0.3366	0.0331	0.2143	0.129
2	-0.1377	-0.0546	-0.118	0.0358	-0.1017	0.1201	-0.0908	-0.0207
3	0.0141	0.096	0.0595	-0.1802	-0.0345	0.1999	0.0212	-0.0898

Table 12: Correlation between average windspeeds and tilt data for June 2014.

The tables above display that the correlation between the wind and the sensors is virtually non-existent. And since this were months with exceptionally strong winds, it follows that in the other months the wind should also have left the telescopes unaffected.

Besides calculating the correlation coefficient, all month's data were plotted. The plots also undermine the results of the correlation coefficient. There is just one exception. See figure 18 below.

In the plot for bay 1 for the month of June in 2014 you can see that as the wind increases around the 11th of June the error for sensor one and three increases. This might be caused by the wind. A possible explanation why this is the only instance of the analysed data in which you

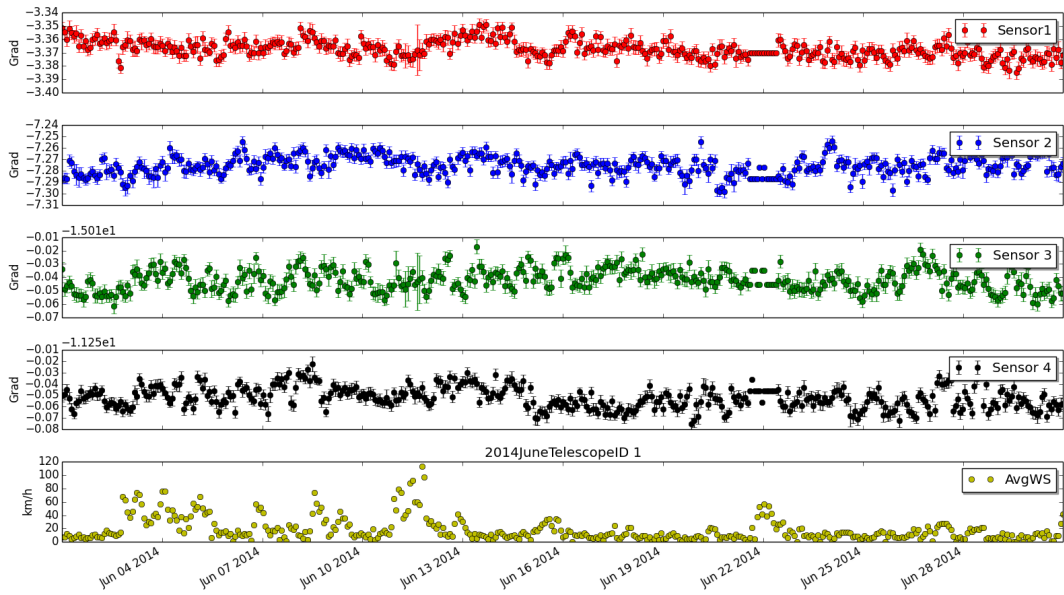


Figure 18: Correlation between the average windspeed and the inclination data. The data was summarized with the algorithm described in the subsection "Temperature".

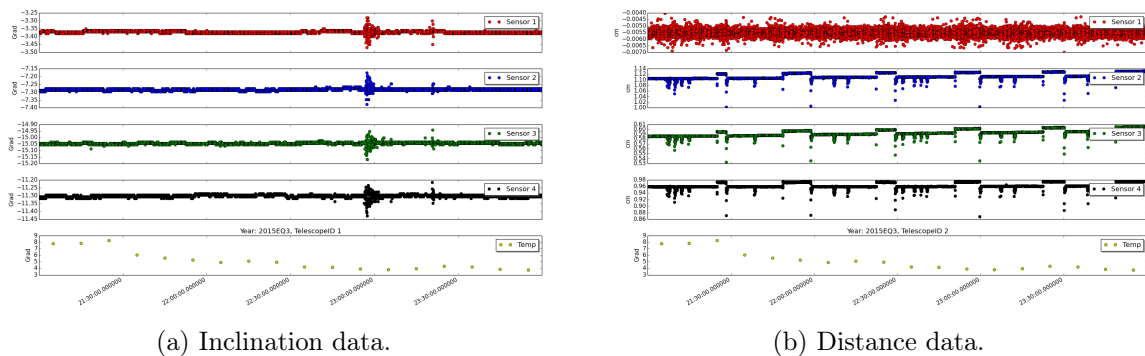
can see the excess might be, that the wind came from an advantageously direction leading to a notable tilt of the telescope.

4.4.3 Earthquake Retrospective

In order to get an understanding how earthquakes affect the tilt data we need to find a strong one.

On the 16th of September 2015 at 22:54:33 UTC there was an earthquake 46 kilometres offshore from Illapel¹⁹ in Chile. With a magnitude of 8.3 and so close to the Pierre-Auger-Observatory it should show in the data.

The following plots in figure 19 show the inclination and the distance data on the 16th of September between 21:00:00 and 00:00:00 UTC. Note that for some reason, which is not explained in the e-log data, there is only distance sensor data from bay 2 and inclination data from bay 1.



(a) Inclination data.

(b) Distance data.

Figure 19: Tilt data around the duration of the Illapel earthquake.

¹⁹https://en.wikipedia.org/wiki/2015_Illapel_earthquake

The earthquakes main tremor and the aftershock with a magnitude greater than six can clearly be seen in the inclination data. The time at which it affected the sensors is also in line with the time given in the wikipedia article (see footnote 20). The dist data doesn't show such clean fluctuations. A possible explanation for the lack of fluctuations in the distance data is that the chassis of the HEATs are very stable. Since the inclination data provides much cleaner data, it will be used to detect earthquakes with an algorithm in the next section.

4.4.4 Earthquake Search Algorithm

Now knowing what normal fluctuations in the data look like and having examined the effects of an earthquake onto the data an algorithm which looks for earthquakes can be written. Since the Illapel earthquake was so clearly visible in the data one might be able to find another earthquake. One of the simplest ideas to look for earthquakes with an algorithm is to scan the inclination data and test the fluctuations in the points. This is done by moving a window through the data which checks for deviations from the mean. I wrote the algorithm in the following way: It checks for each data point, if the point differs more than two standard deviations from the mean. If this is the case for a point and at least four out of the next five points - which physically translates to an interval of five seconds - the algorithm saves these five points and their corresponding datasets and jumps to the next point, repeating the procedure. Obviously already saved point will not be counted twice. Afterwards these saved points are plotted. Note that an earthquake shakes the telescopes heavily and therefore the interval window should't be too large, since the probability of leaving a point out and not spotting an earthquake, because a point is by chance within two standard deviations from the mean, grows with the windows size. Also while the mean can be calculated with a given dataset, the standard deviation should be given. In the examples below according to the examined normal fluctuations a standard deviation of 0.01° is used. This algorithm only works if you use it within one tilt mode.

To test if this algorithm works it was used with the already discovered Illapel earthquake. The result can be seen in figure 20.

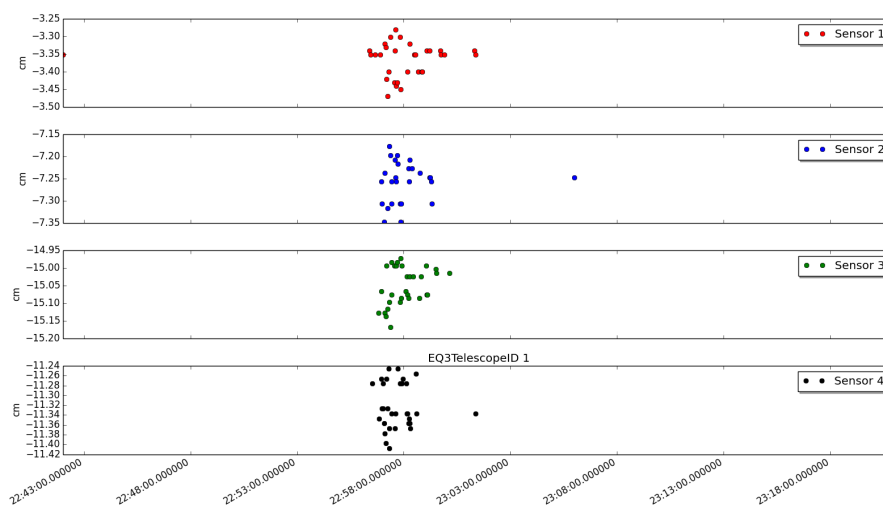


Figure 20: The algorithm successfully discovered the Illapel earthquake.

Figure 20 shows that the algorithm successfully discovered the earthquake.

It was now used on another dataset to see if it can discover other earthquakes. But going through several datasets no other earthquakes were found using the algorithm. To check whether the algorithm is flawed a list of earthquakes²⁰ has been checked. In this list there are two other possible candidates that were in the time frame in which the HEATs were already build. One on the 27th of February 2010 and one on the 1st of January 2011. As it turns out HEAT data wasn't recorded around the 27th of February which disqualifies the 2010 Salta earthquake ²¹. However there is data for the 1st of January 2011. But there are no fluctuations visible in the data around that date.

Note that in addition to the list of earthquakes above other earthquakes around Argentina have been retrospectively checked, too. But these too weren't visible in the data.

A possible explanation for the fact that other strong earthquakes don't show up in the inclination data might be that the earthquakes were either too far away or too deep underground to be noticed at the HEATs' sight.

²⁰For the list used see: https://en.wikipedia.org/wiki/List_of_earthquakes_in_Argentina.

²¹https://en.wikipedia.org/wiki/2010_Salta_earthquake

5 Summary

This thesis provided the reader with a basic understanding of the HEAT's tilting mechanism. It explained the working mechanisms behind the fluorescence detectors together with the basic functions of the HEATs' tilt sensors. In addition to that the sensors' specifications and the ways data is acquired were given.

This thesis also showed how to access and read out the tilt monitoring data. It introduced the basic functions of MySQL and showed how to access the data through the browser and with Python.

In the analysis the tilt monitoring data was examined. Since the HEATs have been running with only a few relatively small interruptions since 2009 there has been collected a lot of tilt monitoring data. Even though this thesis could only examine a small part of the data the results look very satisfying. The data from the HEAT sensors is very stable. The HEATs' chassis seem to be very solid since there is almost no correlation between the different inclination sensors' axis. Furthermore the shifting process is very precise in that it doesn't change the variances of the sensors. But this analysis showed that the HEATs don't tilt full 30 °, but 29 °. As far as the weather is concerned there are only small variations in the data. The temperature has only a little effect on the inclination sensors and a little stronger effect on the distance sensor. As stated in the corresponding section this is likely because the potentiometers are attached to cables. The wind also leaves the HEATs unaffected, if it isn't exceptionally strong and blowing from an advantageous angle. The only thing showing up in the data is the strong Illapel earthquake. In fact this earthquake was so distinctly displayed by the data, that it led to the conclusion that the inclination data could be used to discover earthquakes in retrospective. However this assumption could not be verified as the only other candidate for an earthquake in Argentina didn't show up in the data. The same applies for strong earthquake in the area around Argentina.

Further research could take into account larger quantities of the data to further examine the questions of this thesis.

6 Acknowledgements

First of all I want to thank Professor Hebbeker, who gave me this thesis basically "last minute" and took time almost every week to guide me. Secondly I want to thank Dr. Oliver Pooth for being the second assessor.

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7 Appendix

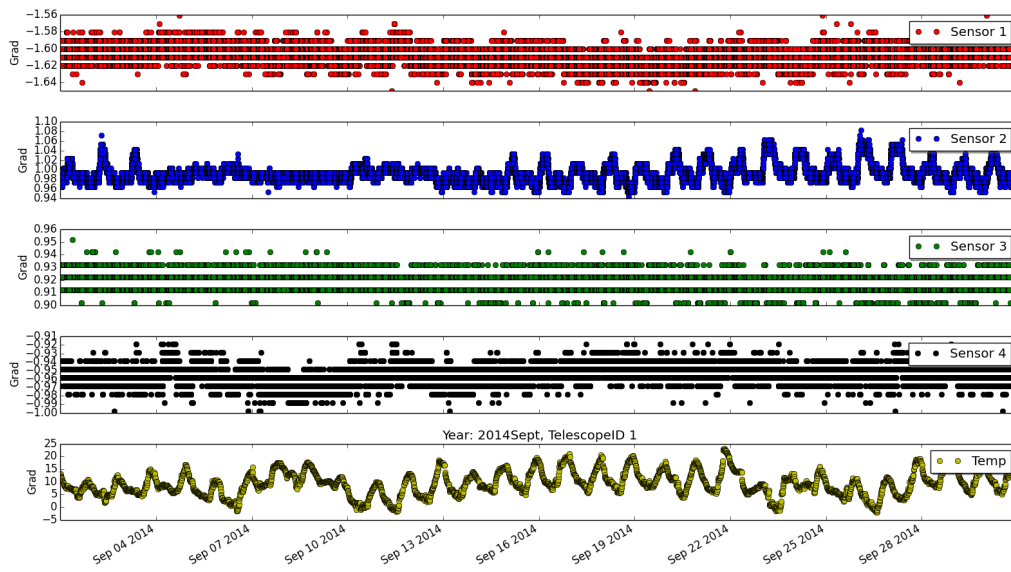


Figure 21: Y-sensors Bay 1, year 2014, month September.

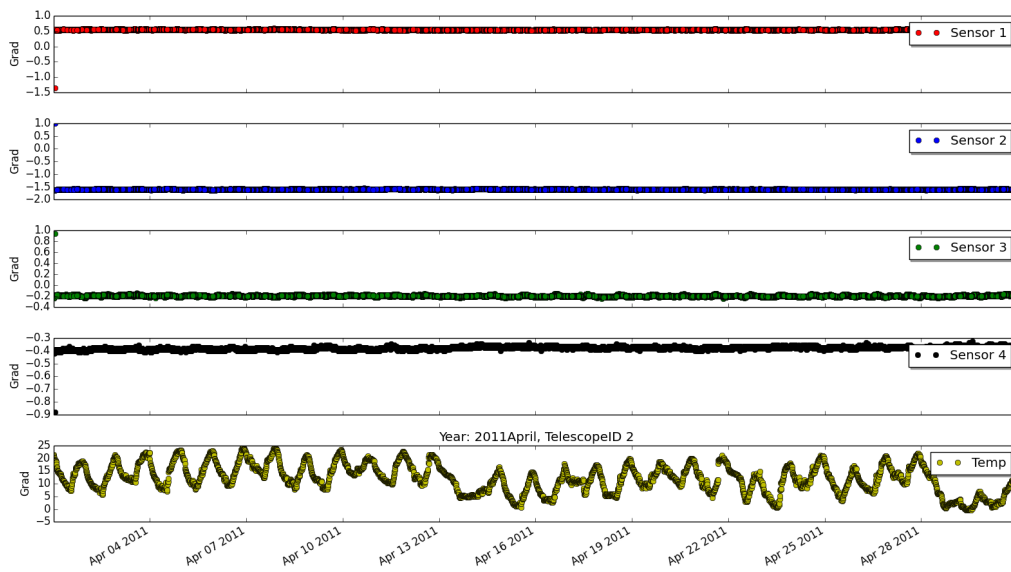


Figure 22: Y-sensors Bay 2, Year 2011, Month April.

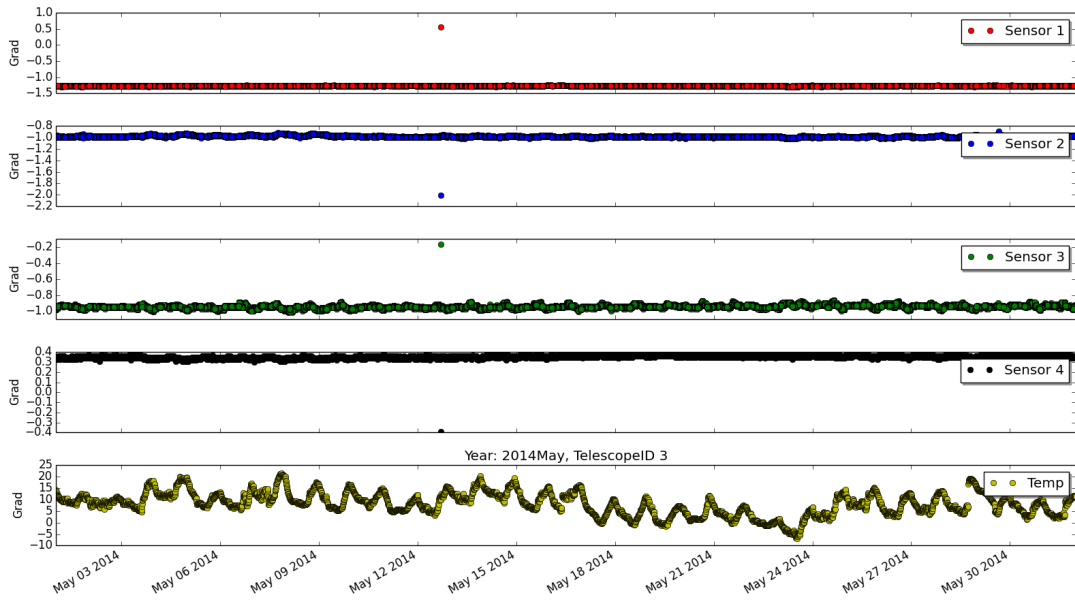
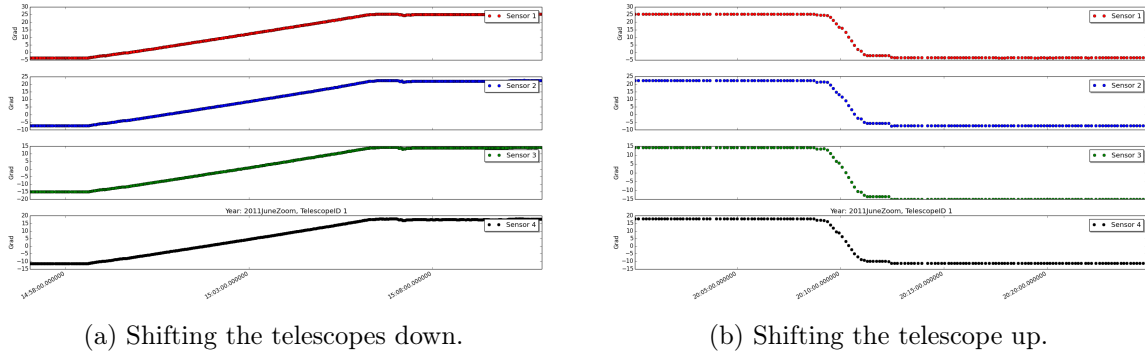


Figure 23: Y-sensors Bay 3, Year 2014, Month May.



(a) Shifting the telescopes down.

(b) Shifting the telescope up.

Figure 24: Shifting of bay 1 in June 2011. Keep in mind that the lower values are actually the "upward" mode.

ID2	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	0.863	-10.613	1.162	-14.448	1.397	-15.685	0.888	-13.319
Variance	0.866	0.010	0.464	0.010	0.208	0.013	0.170	0.007

Table 13: Bay: 2; Pre-Shift.

ID2	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	0.884	18.411	1.143	14.498	1.399	13.374	1.053	15.605
Variance	0.888	0.008	0.517	0.008	0.207	0.009	0.069	0.007

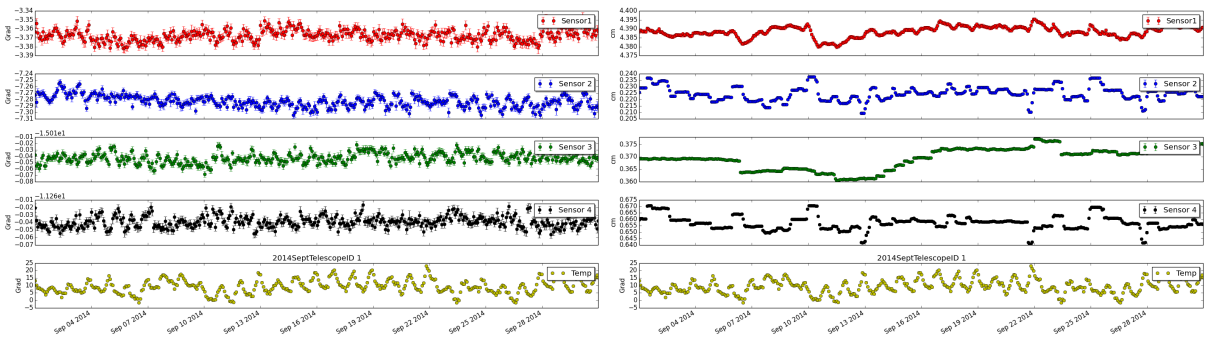
Table 14: Bay: 2; Post-Shift.

ID3	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	1.728	-263.245	0.699	-10.228	1.189	-7.654	0.72	-13.506
Variance	0.005	0.009	0.008	0.009	0.004	0.014	0.037	0.007

Table 15: Bay: 3; Pre-Shift.

ID3	Dist 1 [cm]	Inc 1 [°]	Dist 2 [cm]	Inc 2 [°]	Dist 3 [cm]	Inc 3 [°]	Dist 4 [cm]	Inc 4 [°]
Mean	1.771	861.548	0.627	18.891	1.192	21.591	0.991	15.549
Variance	0.004	0.007	0.008	0.016	0.004	0.018	0.038	0.010

Table 16: Bay: 3; Post-Shift.



(a) Inclination data.

(b) Distance data.

Figure 25: Plots showing the summarized data used to calculate the correlation between the distance/inclination data and the temperature.

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