An Observation Station for Geomagnetism and Geomagnetic Storms – A Project in a Research Club

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Kurzfassung

Geomagnetismus ist wesentlich zum Schutz vor kosmischer Strahlung. Geomagnetismus fördert das globale Denken sowie globale Vernetzung und bietet daher substantielle didaktische Perspektiven. Wir berichten über ein entsprechendes Projekt in einer Jugend forscht AG und über verallgemeinerbare Erfahrungen. Unser Projekt befasst sich mit der hochpräzisen Aufzeichnung des Erdmagnetfeldes. Die Sonne hat einen großen Einfluss auf die Schwankungen dieses Feldes. Um diese Schwankungen im Erdmagnetfeld aufzuzeichnen, haben wir eine Messstation errichtet. Dabei haben wir besonders auf eine störungsfreie Umgebung geachtet, um hochgenau aufzuzeichnen. Anfang November 2021 wurde über Polarlichter in Deutschland, verursacht durch eine große Sonneneruption berichtet. Diese können moderne GPS- und Kommunikationstechnik stören. Mit unserer selbstgebauten Messstation konnten wir eine deutliche Veränderung des Erdmagnetfeldes messen, es war die größte Eruption, die ich bisher aufgezeichnet haben. Das ist einer von vielen Sonnenstürmen, die wir aufgezeichnet habe. Durch Vergleiche konnten wir zeigen, dass unsere Station die Sonnenstürme präzise aufzeichnet. Die Soft- und Hardware der Messungen wurde in mehreren Entwicklungsschritten verbessert, u.a. im Bereich Informatik.

Abstract

Geomagnetism is essential for protection against cosmic rays. A project in geomagnetism develops global thinking and global networking. So, such a project provides substantial didactical perspectives. We report on such a project at a research club and on corresponding experiences. Our project deals with the high-precision recording of the earth's magnetic field. The sun has a great influence on the fluctuations of this field. In order to record these fluctuations in the earth's magnetic field, we have set up a measuring station. We paid special attention to an interference-free environment in order to record with high accuracy. In early November 2021, auroras were reported in Germany, caused by a large solar flare. These can disturb modern GPS and communication technology. With our self-built measuring station, we were able to measure a significant change in the Earth's magnetic field, it was the largest flare we have recorded so far. This is one of many solar storms we have recorded. Through comparisons, we were able to show that our station accurately records solar storms. The software and hardware of the measurements were improved in several development steps, including computer science.

1. Introduction

An observation station for geomagnetism and geomagnetic storms can exhibit a substantial didactical potential. In order to realize it, we analyse the didactical perspective.

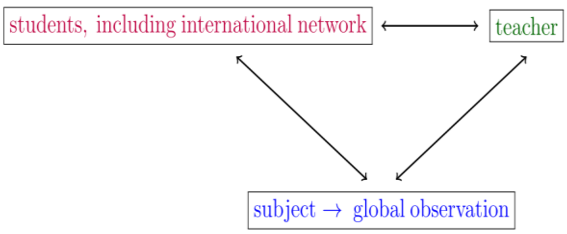

Fig. 1: Didactical triangle. In challenging global observations, international networks of students are appropriate

1.1. Didactical perspective

Students are highly interested in astronomy and astrophysics (Elster 2010, Jenkins 2006, Pössel 2015). A striking property of space is its astonishing size. Thus, the question arises, what physical objects can fill huge areas in space, as masses are relatively small. The fields of the weak and of the strong interaction as well as the electric field are shielded and have little extension, as a consequence. However, the magnetic field can hardly be shielded, so that it extends to huge regions of space. For instance, Earth's magnetosphere has a size of six diameters of Earth, at least. And the Earth's magnetic field is only stopped by Sun's magnetic field at the magnetopause (e. g. Carmesin et al. 2020, p. 84-91, 125, 132-133, 139). Moreover, Earth's magnetic field is essential for life, as it protects us from the cosmic radiation. Accordingly, the student's interest in magnetic fields in space has a substantial didactical perspective. The didactical perspective can be analysed in the framework of the didactical triangle, see Franke and Gruschka (1996) or Fig. 1. That triangle represents the relation between the students, the teacher and the subject. Hereby, the relation between the students and the subject is characterized by a high interest. Moreover, Earth's magnetic field is caused by the complicated geo-dynamo, that field is exhibited to solar storms, and so, that field has complex dynamics. Thereby, even reversals of Earth's magnetic field are possible (Brunhes, 1906).

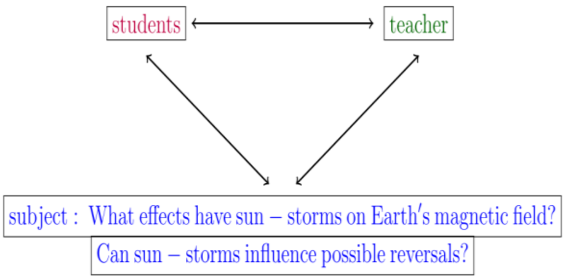

Fig. 2: Didactical potential: scientific question.

Accordingly, a wide understanding of the dynamics of Earth's magnetic field, including reversals, is very challenging, see Fig. 2. So, it can only be achieved in the future. In particular, it requires a global and international network of many measurement stations. Such a network could in principle be organized by learners at schools. Correspondingly, the subject could become interesting for learners and for science teachers, if a fully developed measurement station would be available, and if that station could be easily reproduced, implemented and driven, see Fig. 3.

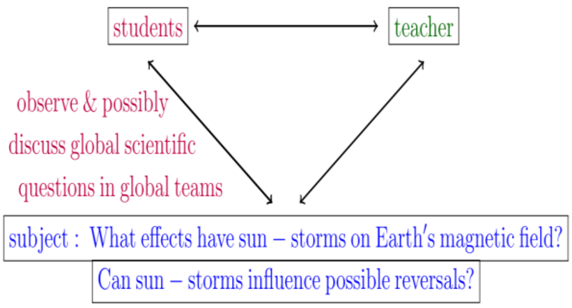

Fig. 3: Didactical perspective: global scientific network is possible.

At such a network of stations, students can develop various key skills: teamwork, experimentation, application of information technology, finding and testing an appropriate site with little magnetic pollution, implementing and managing an observation station, evaluating of observations, physical modeling of fields and particles.

In global observations, networks can be appropriate. For instance, Backhaus, Gabriel and Kersting (2014) organized an international network of students in order to observe a transit of Venus at various perspectives. Based on the results, the astronomical unit was determined.

Another example is the observation of the Big Bang at a school observatory. Hereby, various methods have been applied and several observations have been used. Altogether, a time-network of students performed observations in the years ranging from 2011, see Carmesin (2012) to 2018, see Helmcke et al. (2018) and at the same school observatory in Stade. Hereby, several students have developed useful equipment for the observatory, have presented their results at Jugend forscht competitions and have been awarded with prizes at various levels.

The present project takes place in the framework of a research club. Thereby, the student Florian von Bargen performs the project, and the teacher Hans-Otto Carmesin coaches Florian and oversees the project. Additionally, Florian organized support from various partners, see acknowledgement. Moreover, Florian takes part in the astronomy club provided by Hans-Otto, where Florian communicates the progress of his project.

Using his developed observation station, Florian was able to obtain high level observational results, including the discovery of a filament that occurred at a magnetic storm. So, the didactical perspective of the project has been tested. Thereby, the station proved to be productive at an advanced level.

1.2. On solar storms

The sun constantly sends radiation and charged particles into space. Besides light particles, the photons, it also emits charged particles. The latter steady stream of particles is called solar wind. In the uppermost and hottest solar layer, the particles heat up strongly and can thus overcome the gravitation of the star. These particles are mainly protons and electrons, which shoot into space at speeds of 400 to 800 kilometers per second. One speaks of a solar flare when this current is significantly stronger than usual for a short time and in a limited area. The radiation and particles produced by a solar flare travel through space and can also strike the Earth. The subsequent phenomena that are set in motion there are called solar storms (Karrtunen et al. 1996, Ambastha 2003, Roberts and Glatzmaier 2000).

The plasma cloud moves through space at speeds of up to 1000 kilometers per second and thus it takes about one to two days before it reaches Earth. The bulk of the particles, however, are slower and therefore take longer. The plasma cloud is responsible for many of the effects observed on Earth during a solar storm. Earth's magnetic field is so large that solar storms are mostly shielded, but occasionally solar storms are strong enough to break through it. At the equator, the Earth's magnetic field has a strength of about 0.03 milli Tesla = 30 micro-Tesla (Source 4). At the poles, the value is about twice as high. For comparison, the value in northern Germany is 50 MT.

Near the poles, the magnetic field lines of our planet enter the earth.

The charged particles are deflected by the Earth's magnetic field so that they orbit around the Earth in a ring, the Van Allen belt. The particles deform the magnetic field, depending on the strength of the solar wind. They move along small helical lines around the magnetic field line. Along these lines they can eventually hit the atmosphere. The especially nice side effect is that we can then see this as auroras in the polar regions.

1.3. **Idea**

Solar storms can have a great impact on our life on earth. The high energy particles have an ionizing effect and are able to cause unwanted electric currents.

Due to the high energy particles, power lines can overload (see e. g. OECD, 2011). Circuit breakers installed in houses to protect against overvoltage damage are therefore mandatory in Germany. Violent solar storms can cause power outages, erase data from hard drives, and paralyze satellites and air traffic. This would lead to unpleasant restrictions in our daily lives, and cause high costs. In 1989, a violent solar storm in Quebec, Canada, shut down the power grid for nine hours. Such a blackout can have severe consequences, e.g., in the power supply of important facilities such as hospitals and airports. High costs and/or insurance claims can also arise for the economy due to outages or damage to production or the transport of goods.

In 2012, a solar storm narrowly missed Earth; according to studies, this solar storm would have had twice the force of the 1989 storm in Quebec. The probability of a "super solar storm" is 12% from 2014-2024. How great the consequences and damage to civilization would be is hard to estimate; science disagrees.

Reversals of polarity can also be observed in the normal long-term behavior of the Earth's magnetic field. However, these occur over very long-time spans of several thousand years.

Being able to measure and perhaps predict solar storms is more important than ever. After all, our daily lives are very dependent on a steady supply of electricity. As the advancing digitalization replaces manual machines, there is a total dependence on the power supply. In addition, more and more data is being stored digitally. Electricity is needed for these data storage devices. If there is a power failure, it cannot be accessed. This leads to failures in the economy, e.g., in the production of goods, and it paralyzes our working life to a large extent. The difference to conventional catastrophes is that a solar flare affects entire continents, and the repair of a large-scale failure takes months, and vital infrastructure is therefore not available.

1.4. **Goal of the project**

The goal is to be able to measure solar storms on the basis of magnetic field fluctuations with an own sensor. The measured data are then analyzed and evaluated (similar to experiment 1). The mean value of the three directions and the magnitude (x, y, z and magnitude mean value) is formed. These form the basis for predicting the next solar storms. With enough data, an educated prediction on changes in the magnetic field can then be made.

1.4.1. **Means to achieve the project goal**

We will store these measurement data with the help of the sensor FLC3-70 of the company Stefan Mayer Instruments on a Raspberry Pi, with the help of a micro-SD card. The predictions will be supported by other measurements (for example PTB). The measurement with satellites or telescopes, which record the solar activity, also offer a time advantage, because the solar storms reach the satellites first, before they hit our sensor. This also allows a precaution to be weighed in terms of intensity and arrival on Earth.

2. **Experiment 1: Hall sensor**

A magnetic sensor is installed in most smartphones and tablets. The so-called Hall sensor offers an accuracy of 10^{-6} T. An iPad Air of the 1st generation (2013) was used as a sensor in our first test. The tablet was placed in a weatherproof plastic box with a charging cable. The app "phyphox" from RWTH Aachen was opened, and the measurement "magnetic field" was started. From then on, the device measured all magnetic changes on the x/y/z space. The box with the tablet was fixed to the outside of the roof truss of the house to get better results.

2.1. **Digital method**

The "pyphox" app records the data, and then you can export it as an evaluation file. The measurement takes place 100 times a second.

2.2. **Measuring principle of the Hall sensor**

A current is injected through two opposing electrodes. Two orthogonal electrodes then measure the Hall voltage. The output voltage is proportional to the magnitude of the vector product of B-field and velocity. The temperature can influence the vector product.

2.3. **Results of experiment 1**

In the first test with the tablet magnetic sensor (Hall sensor), the measurement results did not turn out to be precise enough. The Hall sensor measures magnetic field fluctuations in the range of micro-Tesla. However, most solar storms only cause a magnetic field fluctuation of a few nanotesla. In the professional measurements of PTB, this fluctuation is partly several 100 nanotesla, which can therefore no longer be measured with the Hall sensor. To be able to measure a magnetic field change with the Hall sensor, therefore, a very strong solar storm would have to occur, which is very rare. Therefore, we concluded that another sensor is needed to measure the required nanotesla variations.

3. Experiment 2

All problems, which were noticed in the first test, indicate that the measuring data do not show a purposeful precision. Therefore, we decided to use a sensor from the company Stefan Mayer Instruments. This terminal FLC3-70 was provided to me on 04.01.2020, and this one provides high resolution measurement data in the range of nanotesla.

A second and third FLC3-70 were provided to me on 02/14/2020. A sensor was set up on 22.02.2020 in Bielefeld at relatives. The experimental setup there is not different from the one in Stade. This second location will be used to visualize and evaluate the difference of the measured magnetic field value. The data of both locations are entered into an Excel file. With this now existing basis it is possible to show a public presentation of the measurement results, similar to the measurements of the PTB, and to make them available to third parties. The third sensor was also installed in Stade to control the sensor there.

3.1. Setup

The decision for a developer board was then an Arduino or a Raspberry Pi. Since the sensor works on 16-BIT, the choice fell on a Raspberry Pi, which can process this reliably. We use a Raspberry Pi 4 Model B together with an analog/digital converter from joy-it. Previously, we tried to program it with an Arduino, which turned out to be not favorable due to reliability and precision. The converter is plugged on a plug-in PCB. This is connected via a Male-Female cable connected to the Raspberry Pi in the correct mapping. The Fluxgate sensor is connected to the converter in a similar way so that the output of the sensor goes through the converter to the Raspberry. The prepared experiment is installed in a case to adequately protect the high-quality components. This setup was repeated for the second and third sensor.

These have to be assigned to the converter first. After that, the cables from the converter are assigned to the Raspberry Pi.

Fig. 4: Fluxgate FLC3-70 sensor from Stefan Mayer Instruments

3.2. Measurement principle: fluxgate sensor

The two cores (Core 1, Core 2) are wrapped by receiver coils. In the absence of a magnetic field, the voltage is canceled (V=0). Now, when a magnetic field occurs, the saturation of one core is reached earlier than the other. This asymmetry is proportional to the field change and is reflected as a voltage change.

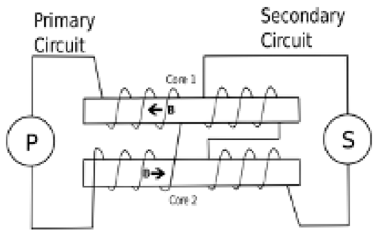

Fig. 5: The measuring principle of the Fluxgate sensor

The sensor shows the measured electromagnetic change in volts with the three voltage values. It is measured in three directions. These are displayed as xv, yv and zv. With the three "raw values" (x-raw, y-raw, z-raw) the corresponding measured values of the voltage changes in the different directions are displayed.

3.3. Method

Now the setup is subjected to some tests which check the results for systematic errors. A part of these systematic errors could already be reduced by the out signal. If these are passed, it is sure that a successful day and night rhythm could be recorded. The recording of the PTB was used as a reference. The day and night rhythm shows fluctuations in the range of 1‰.

3.4. Results of experiment 2

The FLC3-70 sensor from Stefan Mayer Instruments allows high-resolution measurement data in the range of nanotesla. The magnitude is the result of the combined values: x-raw, y-raw, z-raw. The formula for calculation is:

$(x\text{-raw}^2 + y\text{-raw}^2 + z\text{-raw}^2)^{1/2}$ = magnitude.

The measurement data showed that a collection of measured values of the electromagnetic changes could be successfully made by the two sensors FLC3-70. The stored values could also be successfully saved to the micro-SD card, and shown as measurement data tables and graphs. The results show that the sensors have a systematic measurement inaccuracy, which can be seen for example in the mean value amount. This inaccuracy is much larger than the statistical measurement inaccuracies. The standard deviations here are 5 nanotesla, this is obtained by averaging 300 values recorded in 150 seconds. We interpret this variation as stochastic measurement uncertainty. The systematic measurement inaccuracies, on the other hand, were investigated.

The goal of Experiment 2 was to reduce the systematic measurement inaccuracies to 0.1‰ because this allows highly detailed measurement of the diurnal and nocturnal rhythms. The "two-sensor operation" turned out to be counterproductive, after consultation with the sensor manufacturer, because the coils excite each other, and falsify the measurement result.

3.5. **Construction of an own measuring station**

For further improvement of our measurement data and expansion of our project, we used the procedure and setup of a PTB measurement station as a model, since it records measurement data in an interference-free environment.

3.6. **Measurement in the forest on 29.8.2020**

In order to be able to achieve similar results as the PTB, we also looked for an environment as undisturbed as possible. On 29.08.2020 we then carried out a measurement in a nearby forest. There, lower interference fields are to be expected as in the experiments before. The measurement was set up on a polystyrene plate in order to minimize vibrations of the ground and thus the influence on the results. In addition, the box was weighted to eliminate minimal movement, such as that caused by wind. The power is supplied by a mobile power bank, which is placed one meter away from the measurement, as a lithium-ion battery also causes minimal interference fields. The measurement results show that the suspicion has been confirmed that civilization has a disturbing influence on the accuracy of the measurement. To ensure the most natural representation of the earth's magnetic field, a stationary measuring station has been set up outside the known interfering factors. This lets expect much better results than a mobile station, because a long-term course can be recorded.

4. **Stationary measuring station**

During the search for a stationary location and also during the construction of the station, the factors for a measurement as uninfluenced as possible had to be considered. To ensure this, the sensor should be buried at a soil depth of 80cm. In 80cm soil depth the temperature fluctuations are reduced, furthermore no weather-related disturbances are to be expected for example by wind, rain and hail. Minimal positional changes due to wind gusts are also reduced, such as those that occurred when the system was installed on the roof of a house. The search for a location proved difficult, as an area had to be found that was 80 meters away from built-up areas and other disturbances (high voltage, cars). In addition, a power supply and an Internet connection had to be guaranteed. To find a suitable environment, we made series of measurements at possible locations under consideration of the distance to the buildings. These took place on 6. and 9. September at a field way in the Bützflethermoor in Stade. The recorded data were promising, so the location seemed to be suitable for recording the magnetic field. The area around the Bützflethermoor is very suitable, since it is sparsely populated, and interference fields from the population are reduced to a minimum. The jury of the Celle 2021 regional competition subsequently pointed out to us that at the measurement station could interfere with the magnetic field. As a result, on 20.02.2021 we contacted EWE, the regional electricity provider. They provided me the plans of this area. With the help of the information, we could exclude that power lines were buried which would have generated interference fields.

Fig. 6: Own stationary measurement in Stade, German

4.1. **Construction of the measuring station at September 2020**

Then we buried the pipe about 80 cm into the soil. The upper end protrudes approx. 60 cm from the soil, and can be sealed watertight with a lid. On the concrete bottom of the pipe lies the Fluxgate sensor in a box with the necessary accessories. The cavity between the floor with the sensor and the lid was filled with foam as insulation to achieve a constant temperature of the sensor.

For the power and internet supply we decided to use a PoE (Power over Ethernet) cable. This is inexpensive and allows power and internet to be transmitted over one cable. The advantage is that only one cable has to be installed to provide power and internet for the data export. PoE technology uses a PoE injector to supply power. A PoE-capable end device is required to draw power and Internet via one cable. The Raspberry Pi 4B is PoE capable only after an upgrade. Therefore, we decided to use a PoE splitter. This splits the power and the internet again to two different cables.

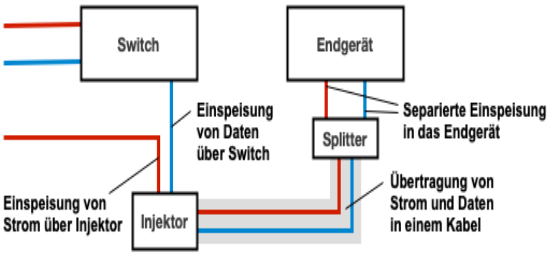

Fig. 7: The PoE scheme

After that we installed a 100m long Cat 7 Ethernet cable, which is PoE capable. Before this could be connected, we had to connect the cable to network plugs. The PoE technology had to be installed in a weatherproof way at the beginning of the cable.

4.2. Weatherproof box on the garden socket on the property

At the garden socket we put a weatherproof box for the required equipment and insulated it with foam. The contents are a PoE-capable uninterruptible power supply, which can supply the measurement without interruption for a few hours in the event of a power failure, until the power grid is available again, as well as a power-line adapter. These are powered by a power strip. The powerline adapter transmits Internet via a WLAN connection from the house into the cable's power grid to the consumer. An Ethernet cable leads from the adapter to the uninterruptible power supply. This converts power and internet connection for the 100m long PoE cable up to the sensor in the measuring station. The built-in UPS supplies up to 48V and 24 Watt, which is sufficient for the Raspberry Pi. However, a part of the current is converted into heat via the 100m Ethernet cable, so 22.4 watts still reach the Raspberry. The Raspberry consumes 4.4 watts in idle mode and 7.6 watts at maximum load. We assessed the risk based on DIN VDE 0100 part 410 protective voltage up to 60 V DC and found no risk.

4.3. Weatherproof box with the sensor in the measuring station

The sensor with Raspberry Pi was also stored in a weatherproof box. The PoE cable ends in the box at a PoE splitter. This splits power and internet to two different cables. This box was then lowered into the pipe. Since the fluxgate sensor is sensitive to temperature and the measurement data may be distorted, the remaining cavity of the tube was filled with foam. To prove the validity of the results, a DS18B20 temperature sensor was attached on December 29, 2020. This provides information about the temperature curve in the box and helps to examine the measurement results.

4.4. Method

We can now correlate the data of our measuring station with those of the PTB to calculate the percentage accuracy and similarity of the measured data (Fig. 9).

4.5. Programming

For the programming of the stationary station, we could use a lot from the program of experiment 2. But in order to carry out the installation of the further complicated program changes we looked for support. Finally, through computer science class, we got in touch with a student with Python knowledge who is doing a similar programming project, so we benefit from each other. Since 10/11/2020, we have been discussing the next steps of programming, which we then implemented. Since the installation of the measuring station, it reliably delivers measurement data, which we can read and evaluate from home via a remote desktop connection. In doing so, we used the TeamViewer client until Jan. 5, 2021, but it frequently terminated after the Raspberry rebooted. This is a severe problem, because we have a 20-minute drive to the measuring station. To be able to guarantee a more stable connection, we switched to RealVNC viewer. This is more reliable on the Raspberry than TeamViewer. In addition, the source code is open source, so it is publicly available. But in the long run these solutions are time consuming. Therefore, we have introduced a log system, which stores every single value. This is necessary to assess the quality of each value. When evaluating the data, the raw data can serve as a backup. This will provide stability for future longer measurements.

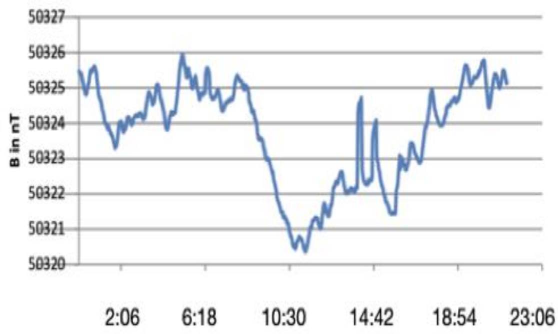

Fig. 8: The daily averaged course of our station

The program measures twice per second. After 120 values or 60 seconds, the measured values are averaged and entered into the table. This is done to reduce statistical errors, and thus averaging leads to a more accurate result. In addition, the Python program records the temperature and RAM usage. This data is important to get an insight into the environmental conditions of the measurement.

The Python code currently in use can be found at: https://github.com/Zyzonix/MGFieldPy/. Furthermore, a status page is available, which provides additional information in case of a malfunction: http:// status.florianvonbargen.de/.

5. Results of the stationary measuring station

The data analysis is done as follows: first it must be calculated how many values correspond to one day (24 hours). Since there is a value every 75 seconds, it takes 1152 values for 24 hours. Then the values were numbered. Here "diff" is the previously calculated factor of the upward trend, if there is one. The upward trend occurs when the lid of the station is opened and the insulation layer is removed to make hardware changes. Ambient air then flows into the tube, cooling the entire station. As soon as the station is closed again, the air gradually heats up, owed to the waste heat of the Raspberry Pi and solar radiation. With this, we can artificially reduce the upward trend. If we now let these data graphically represent, this shows the daily course of the earth magnetic field. It can be seen that, as expected, the earth's magnetic field is weaker at midday than during the rest of the day. In another calculation to show the overall course of the station, an unnatural break occurred. The measured values fell at once dropped, then plotted the diurnal course again, and after a few days the values jumped to the previous level. This incident was investigated, we hypothesized that a sporadic extraneous field caused the disturbance, since the measurement setup had no faults and all possible causes had been investigated. An incident like this has not occurred again in a year and a half. The graph and the corresponding data with their formulas can be found in the appendix.

In Fig. 8, a clear daily minimum can be seen. Our interpretation is that the solar quiet current, a dynamo which follows the noon position of the sun, is depressing the magnetic field. This is recorded by the station. This effect is strongest at noon. This daily minimum also occurs in the measurements of the PTB, and it is characteristic for the normal daily course of the earth's magnetic field. We use this to correlate our data with those of the PTB. A correlation shows both the differences and the similarities between the two measurements. Differences indicate the different sensors or the differing conditions of the site. To correlate the measurements, we have tabulated the amount of daily minimum from both stations. To achieve this, it is important to record a long series of measurements. To improve the duration and the quality of the recording at the same time proved to be a big challenge, but could be improved over the last months. When we make a correlation, we ask for the PTB data of the needed month. The contact persons of the department Magnetic Measuring Field Technology at PTB, Dr. Martin Albrecht and Dipl.-Ing. Hans Harcken provides me with their data. A correlation of our measuring station with a higher federal authority like the PTB provides a qualitative comparison for the classification of our measuring accuracy. A correlation is an evaluation process to determine and document the deviation of one measuring device (our fluxgate sensor) compared to another measuring device (PTB), which in this case can be classified as authoritative. This subsequently includes the consideration of the determined deviation in the use and interpretation of the measurement data from our sensor for correction to the authoritative measuring device.

A correlation of the amounts of the daily minimum is as to be expected not meaningful enough. The local conditions are too different for that. Therefore, a correlation of the times of the minimum is made.

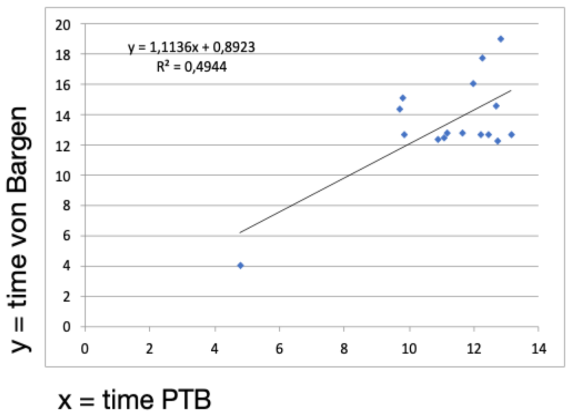

Fig. 9: The correlation of the two stations

5.1. Result on December 2020

A correlation found in December 2020 confirmed for me for the first time that our station can record high resolution - similar to PTB's. On December 23, 2020, our station showed a daily minimum at 3:58. PTB's daily minimum was recorded 49 minutes later at 4:47. The Kp index of December 23 was then used, this shows the geomagnetic activity (for details about the Kp index, see Matzka 2021). The Kp- Index is elevated from 3:00-6:00 UTC (Kp Index 4+). Now one hour is added to this time to calculate the Central European Time (CET). According to these calculations, the Earth's magnetic field was particularly active from 4:00-7:00. This confirms a common correlation of the two magnetic field measurements. Another event was only recorded by our station on December 20, 2020 at 3:38 AM, this one was not recorded by PTB. Another event on December 22 at 0:22, showed only the PTB. For the correlation, we used all daily minima values. For each station there are two values per day. The daily minimum and the corresponding time at which it was measured. Only the time is included in the correlation, because the stations measure different values due to the measurement technique. Thus, a time value of our station is correlated with a time value of the PTB per day. If we remove the two events, which were shown in each case only by one station, we obtain a correlation coefficient of R= 0.70314. If one adds the correlation coefficient to all three events, the correlation coefficient reduced clearly to R= 0.23409.

If all three events are removed, the correlation coefficient is R= 0.16523. The spreadsheets can be found at: http://florianvonbargen.de/downloads/.

5.2. **Result on November 2021**

At the beginning of November 2021 there was a big solar flare. The media reported two days before the impact, additionally that auroras could be seen in Germany. We did not see any auroras at that time, but we did see the magnetic fields corresponding to the auroras. As it turned out, this event was the 44th strongest geomagnetic storm since 1994. Measurement stations were able to record a large anomaly from 3.11-4.11.21, including our station. The KP index on those days peaked at 8-. In comparison, the KP index for the 12/23/2021 event was only 4+. The evaluation showed that this was the largest solar storm recorded by our monitoring station since September 2020.

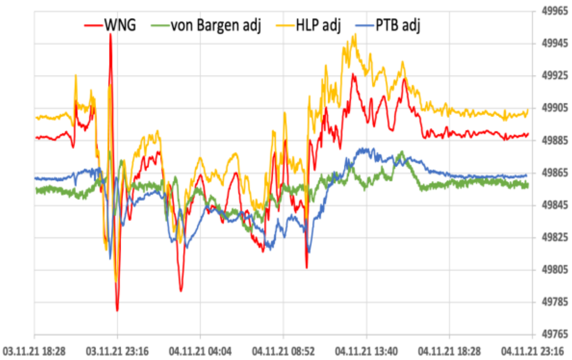

Fig. 10: Magnetic field measurement data of Wingst, PTB, Hel and our station in comparison, period 3.11.21 18:35 - 4.11.21 23:00

In Fig. 10, the event of 3.11 - 4.11.21 can be seen. For the measurement data comparison, the already described station of the PTB was used. In addition, we could find data from two further stations via intermagnet.org. On intermagnet.org there are publicly available data from several hundred stations worldwide. This allows us to compare our data with dozens of stations - only a few hundred kilometers away from our station - and to check for correlations. Above are the measurement data of the PTB, the station Hel in Poland and the data of Wingst, a measuring station not far from our station. The stations measure different values, which are due to the location and the different measurement methods. The changes caused by the solar storm can be seen well. Similar is the green graph - our measurement. The measurement data of the measuring stations in Wingst, Hel and from PTB are comparable with our measurement data. It is noticeable that the four stations show a large temporal variability. Also, the comparison with the station in Wingst, which is only a few kilometers away from our station, shows large temporal shifts of partly more than 5 minutes. We did not expect this so clearly. The comparability of the four stations turns out to be very favorable for an interpretation or analysis of our measured data. Thus, also the temporal variabilities can be broken down better and more exactly. By this groundbreaking finding, further analyses of the four stations can be compared.

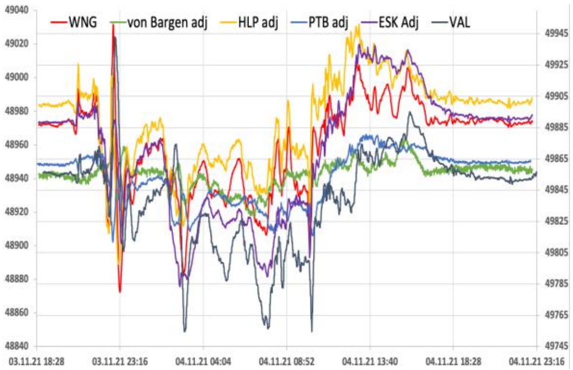

Fig. 11: The event of the 3.11.21 - 4.11.21, extracted: the time difference between the stations

In order to be able to represent the event itself well, and to investigate the factor of the time delay, we have subtracted in a stack plot the time difference of different stations of the 53-55th latitude. Our measurement station served as a reference value; all other stations were assigned to our station based on their measured data history. To the known stations are added two observatories from England: Valentia and Eskdalemiur. All results shown and the graphs can be found at: http://florianvonbargen.de/downloads/.

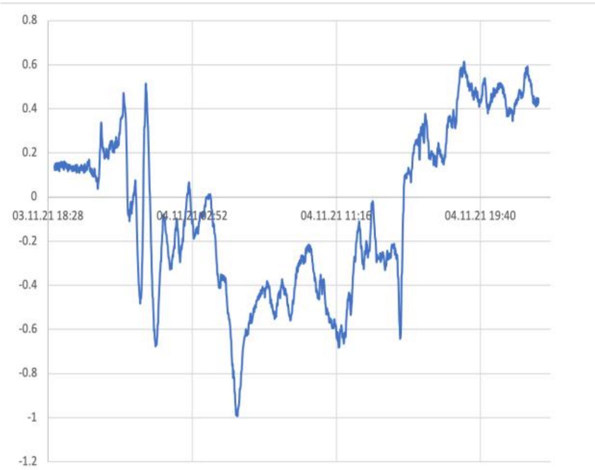

Fig. 12: averaged normalized deviation

The results from Fig. 11 are very interesting. All stations show an amazingly similar deflection when the time difference between all stations is subtracted. A very similar change is recorded to the minute, even though the stations are up to 1317 km apart! This leads me to conclude that this solar storm hit the earth in a very centered way. Thus, the charged particles do not disperse as they travel through space. This let us conclude that there is a self-focusing effect, which ensures that all stations have an almost equal course measure. If this were not the case, the graphs would not run as similar as seen here. At 1317 km distance we would have expected a visible change in the course of the measurements, but this was not so in this case. We will include other observatories, which are farther away than the currently used ones, in a comparison to verify this observation. The mentioned observations and the fact that all stations show a similar measuring course lets us conclude that this event has moved like a filament over the earth. To support this thesis, we have made another correlation (Fig. 13).

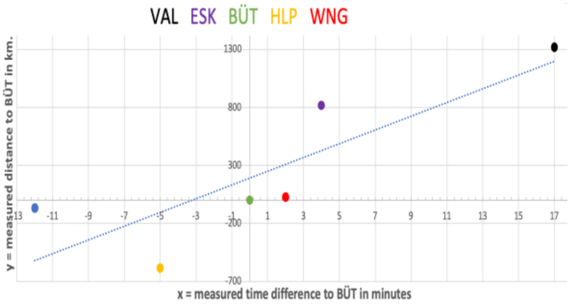

Fig. 13: Examination of the filament with the help of a correlation

To create this correlation, we measured the distance of the stations to our station on the longitude of Stade. In addition, the time difference is measured at the visually displayed course of the measured values as described before. We can see here very clearly that the solar storm has moved steadily for hundreds of kilometers.

5.3. Evaluation of the data

Firstly, for each station $\boldsymbol{S}$, the time evolution $\boldsymbol{B_S(t)}$ has been shifted in time, so that it fits best to the time evolution of the field $\boldsymbol{B_S(t)}$ measured in Stade. So, the shifted time evolution $\boldsymbol{B_{S,shift}(t)}$ has been obtained, see Fig. 11. Moreover, a time shift $\boldsymbol{\Delta t_S}$ is obtained for each station. Additionally, each station $\boldsymbol{S}$ has a distance $\boldsymbol{\Delta x_S}$ from Stade.

Secondly, the shifted time evolution of all measurement stations shows the pattern of the time evolution of the magnetic field during the magnetic storm. The averaged pattern is shown in Fig. 12. Hereby, the shifted time evolution $\boldsymbol{B_{S,shift}(t)}$ of the magnetic field of a station $\boldsymbol{S}$ has been evaluated as follows:

- The average $\boldsymbol{\bar{B}_S}$ has been determined.
- The average has been subtracted, in order to obtain the deviation of the magnetic field: $\boldsymbol{B_{S,dev}(t) = B_{S,shift}(t) - \bar{B}_S}$
- The maximum of that deviation has been determined: $\boldsymbol{B_{S,dev,max} = max(B_{S,dev}(t))}$
- The deviation has been normalized: $\boldsymbol{B_{S,dev,norm}(t) = B_{S,dev}(t)/B_{S,dev,max}}$

Then the normalized deviations $B_{S,dev,norm}(t)$ of the stations S have been averaged with respect to S, and for all times t. As a result, the averaged normalized deviation as a function of time has been obtained: $\bar{B}_{dev,norm}(t)$

Thirdly, the distances Δ_S represent the locations of the pattern of the storm at a relative time Δt_S. Accordingly, we present the function $\Delta_S(\Delta t_s)$ in Fig. 13. A linear regression provides the velocity v_{storm} of the pattern of the magnetic storm relative to the ground. We obtain $v_{storm} = 5145 \frac{km}{h}$.

5.4. Interpretation

In this section, we derive a founded interpretation of our results achieved for the magnetic storm from November 2021.

Firstly, the pattern in Fig. 12 does not have a terrestrial origin, as the equator of Earth exhibits a velocity of $\boldsymbol{v_{Eq} = \frac{40000km}{24h} = 1667 \frac{km}{h}}$, and as the magnetic storm has a much larger velocity $\boldsymbol{v_{storm} = 5145 \frac{km}{h}}$.

Secondly, the storm has solar origin, as it is correlated to a well-known event at the sun.

Thirdly, the storm cannot be explained by a simple particle shower coming from sun to Earth. The reason is that the velocity of Earth at its orbit around sun is $\boldsymbol{v_{orbit} \approx \frac{150 \cdot 10^6 km}{365.24d} = 17112 \frac{km}{h}}$. Moreover, the magnetic storm has been observed at 22 pm, so that the observed storm must have been transported to the night side of Earth. Such a transport can only be achieved by the magnetic field of Earth.

Fourthly, the pattern has a duration of $\boldsymbol{\Delta t \approx 1h}$. Thus, it has an extension of $\boldsymbol{\Delta x = v_{storm} \cdot \Delta t \approx 5145\ km}$. So, it is localized above the ground, as Earth has the clearly larger diameter of 12742 km. Hence, the storm has the spatial structure of a broad filament.

Fifthly, we propose to search for such patterns of the storm at the whole area from Sun to Earth and to the ground of Earth, in future magnetic storms. When the corresponding patterns can be observed in that area, then the origin of the storm can in principle be identified. For it, we identify two main hypotheses:

Either, the origin of the storm can by described by a particle shower, whereby essential magnetic fields occur only in the magnetosphere of Earth. Or the origin of the storm is formed by particles that provide a significant magnetic field in the magnetospheres of Sun and of Earth. In particular, a filament constituted by particles and by a significant magnetic field might form at the Sun, propagate towards Earth, interact with Earth's magnetic field and eventually reach the ground of Earth.

6. Discussion of various obtained results

The correlation allows us a very valuable kind of analysis. The events on 12/23/2020 and 11/3 - 11/4/2021 stand out in particular. Both events proved how accurate our station can record the Earth's magnetic field. The improvements in the accuracy and robustness of the measurement have contributed greatly to this. Correlations and comparisons of the magnetic field measurements with those of PTB and the station in Wingst confirmed the validity of our data. The large effects of the solar storm itself are well documented, the further course shows differences between the four stations. These will be investigated in the following events. The new measurement data comparison with Wingst, PTB, Hel will be kept, because interesting results occurred. There is currently no simple or satisfactory explanation for the clear variabilities between the four stations. To be able to classify these results, further events must follow to be able to observe repetitive developments.

7. Outlook

As in the past, the measuring station in Bützflethermoor is still being improved. Especially the programming is still to be improved, this can increase the effectiveness of future analyses and stations. Through an internship at Stefan Mayer Instruments, we were able to gain a lot of new knowledge. For the next development steps, we will continue to consult with Stefan Mayer Instruments. Through Stefan Mayer we have been able to establish contact with Dr. Beggan, who is a professor of geophysics at the University of Edinburgh and has set up a similar series of experiments, again we will continue to maintain contact to exchange ideas.

We would like to extensively investigate the temporal variations, which are very clear from the November 2021 results. That there is such a large temporal variability of the geomagnetic field within Lower Saxony, we did not expect so. In the analysis and interpretation of future measurement series special attention will be paid to this shift. For this investigation the program "INTERMAGNET" is suitable. There hundreds of observatories put their measuring data, thus a large net of stations, distributed over the globe, develops. We would like to use the data of international stations to investigate the behavior of the earth's magnetic field. Our goal is to become part of this program to contribute to the Earth's magnetic field research. To do this, our station must meet a large number of criteria. Therefore, we are working hard to further increase the quality and stability.

Our future goal is to install several measuring stations in order to be able to create an illustrative representation of the different results. As soon as the permanent operation of the measuring station in Bützflethermoor is ensured, another stationary location can be built. This should be built far away from the first station, because the results will then be different. In this way, we can make an important contribution to investigating the temporal shift of different locations in order to be able to derive further findings.

8. Experience with teaching and learning

The observation station has been developed in several years. Thereby, Florian improved his skills and knowledge in physics, information sciences, experimentation and statistics of evaluation of observational data. Moreover, Florian achieved substantial and innovative results. In the course of his project, he won several prizes at Jugend forscht competitions, including a coached stay at the PTB for several weeks.

This example shows, how a student can use an extended research project for advanced learning at his own topic of interest. Moreover, Florian reported about his project at the associated research club and the corresponding astronomy club. Hereby, he improved his communication skills, and the students of the two clubs learnt about the project.

Furthermore, the project addresses an interesting, essential and global scientific question that can be treated with help of a network of similar observation stations. So, the project can be extended to an international network of students collaborating in a global team. Thereby, the dynamics of Earth's magnetic field, including the influence of solar storms, can be investigated. On that basis, the protection against cosmic radiation can be improved. So, in such a global team working at a global question, students can experience, how they can effectively become responsible for the future of our planet, see Fig. 3.

Altogether, the present project is an example for a challenging global observation by students. In a similar project, the distance from Earth to Sun has been measured by combining observations of a transit of Venus achieved at various places at Earth, see

Backhaus, Gabriel and Kersting (2014). In another example, students observed the Big Bang and measured the age of the universe by application of three mutually independent methods and by using the school observatory. Hereby, students gathered observations during the years 2011 towards 2018, see Carmesin (2012) and Helmcke et al. (2018). In such projects, students can develop, manage and apply stations for measurement and observation. Students can plan, perform and evaluate observations. Moreover, students can combine observations provided by networks, in order to derive advanced global results that could not be achieved by a single or local measurement. So, students can develop various skills including teamwork, experimentation, information technology, scientific modeling and global thinking based on local observation.

9. Literature

Ambastha, A. (2003). The Active and Explosive Sun. In: Antia, H. M. et al. (Eds.): Lecture Notes on Solar Physics, Lecture Notes in Physics 619. Berlin – Heidelberg: Springer-Verlag.

Backhaus, Udo; Gabriel, Patrik and Kersting, Thomas (2014): Zwei Methoden zur Messung der Entfernung Erde-Sonne. MNU, 67/2, pp. 68-73.

Brunhes, Bernard (1906). Recherches sur la direction de l'aimantation des roches volcaniques. J. de Phys. Nov 4th serie t. V, pp 705-724.

Carmesin, Hans-Otto (2012): Entdeckung des Urknalls und der dunklen Energie. PhyDid B Internet Journal.

Carmesin, Hans-Otto et al. (2020): Universum Physik, Qualifikationsphase, Niedersachsen. Berlin: Cornelsen Verlag.

Elster, Doris (2010). Zum Interesse Jugendlicher an den Naturwissenschaften. Ergebnisse der ROSE Erhebung aus Deutschland und Österreich. Online-Publication: Shaker.

Franke, Michael; Gruschka, Andreas (1996). Didaktische Bilder als Bilder der Didaktik. Pädagogische Korrespondenz 17, pp 52-62.

Helmcke, Ben J.; Carmesin, Hans-Otto; Sprenger, Lennert and Brüning, Paul (2018): Three Methods for the Observation with our School Telescope. PhyDid B Internet Journal, pp. 55-60.

PTB and Harcken, Hans (2020). The Live Earth Magnetic Field Measurement. URL: https://www.ptb.de/cms/nc/ptb/fachabteilungen/abt2/fb-25/ag-251/live-daten-erdmagnetfeldmessung.html.

Jenkins, E.W. and Pell, R.G. (2006) The Relevance of Science Education Project (ROSE) in England: a summary of findings. Centre for Studies in Science and Mathematics Education, University of Leeds.

Karrtunen, Hannu et al. (1996). Fundamental Astronomy. Berlin – Heidelberg – New York: Springer-Verlag.

Matzka, J. et al. (2021). The Geomagnetic Kp Index and Derived Indices of Geomagnetic Activity. Space Weather 19(5), pp 1-21.

OECD (2011). Geomagnetic Storms. URL: https://www.oecd.org/gov/risk/46891645.pdf. Download 5/2022, pp 1-69.

Roberts, Paul and Glatzmaier, Gary (2000). Geodynamo Theory and Simulations. Rev. Mod. Phys. 72(4), pp 1081-1123.

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