3rd General Meeting of COST Action COSMIC WISPers (CA21106)

9-12 September, 2025, Sofia, Bulgaria

Magnetometry: from single measurements to network of magnetometers

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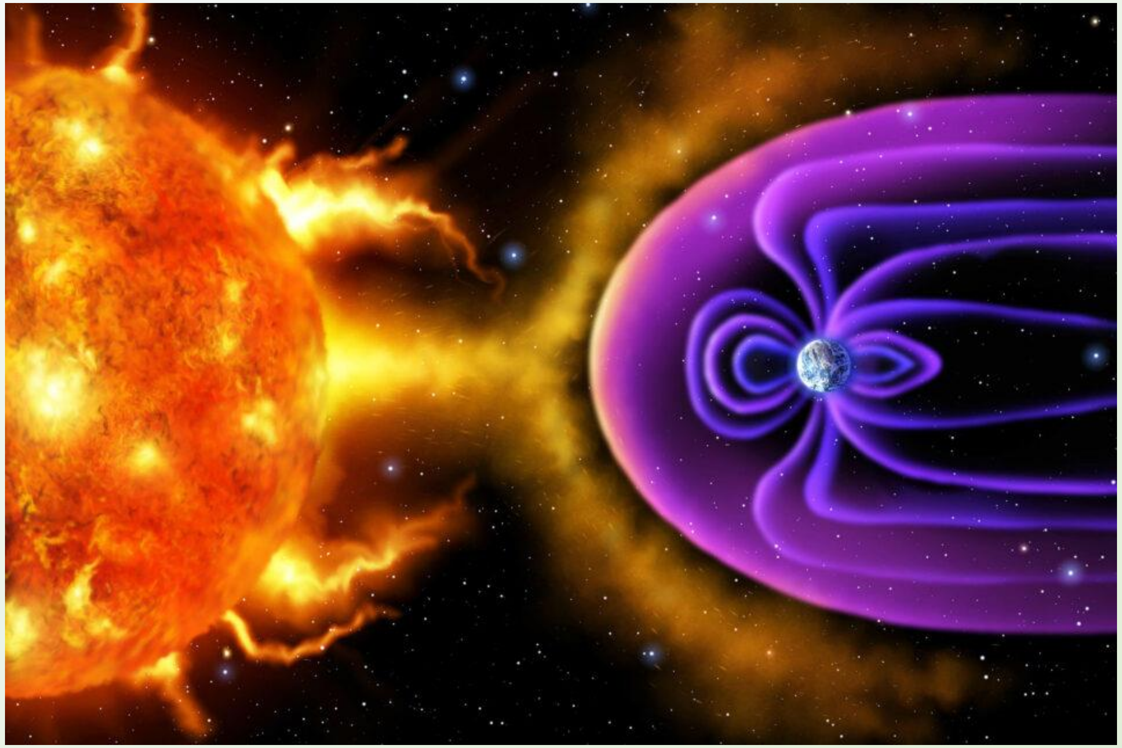
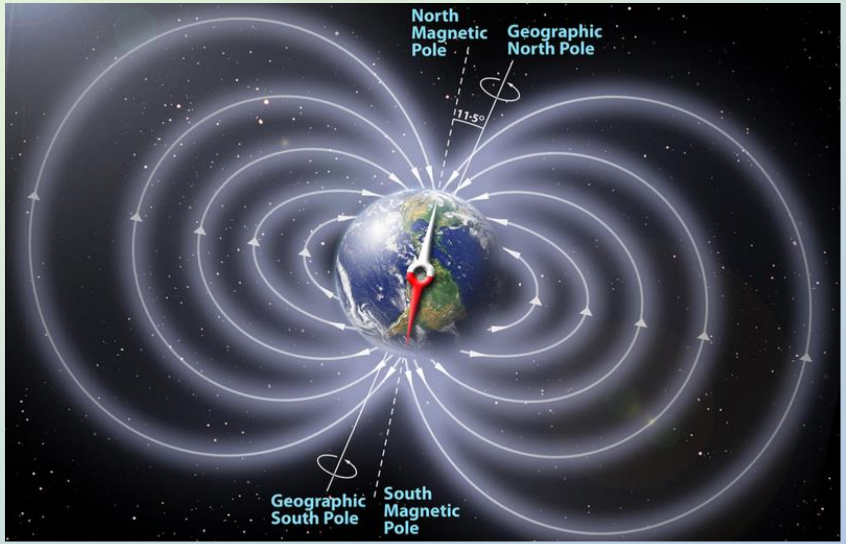
Earth’s Magnetic Field

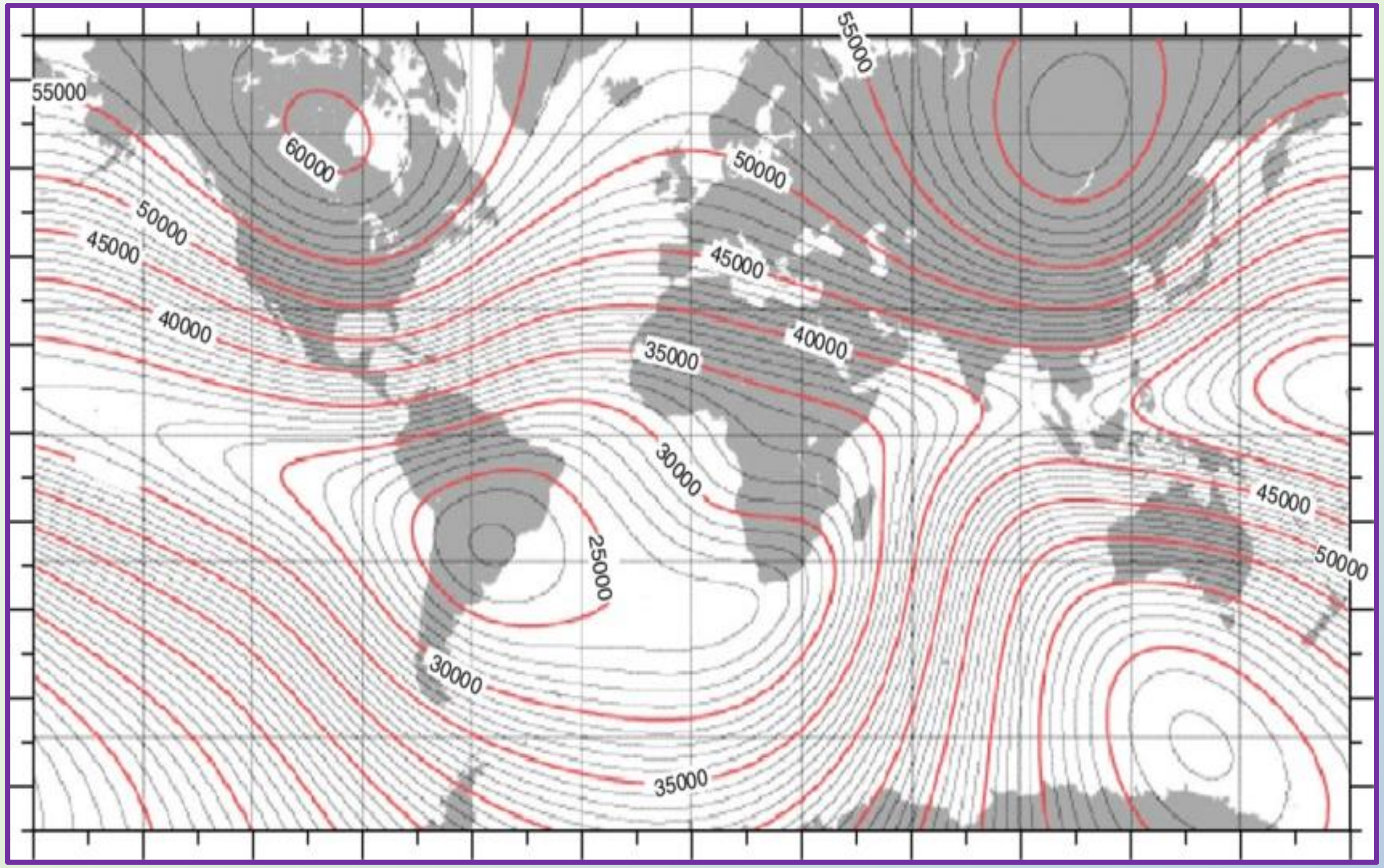


Determines life on the planet and our civilization evolution.



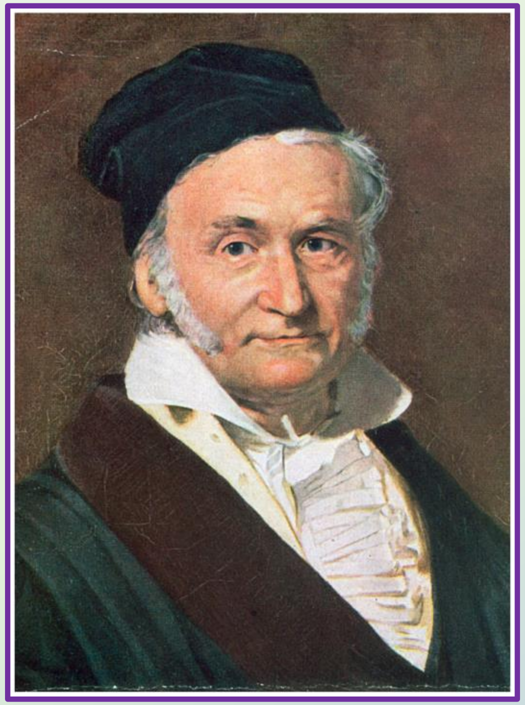
Physics Magazine, American Physical Society

- Geophysical (geological) and archeological surveys.
- Perturbations are ~1nT in both cases!

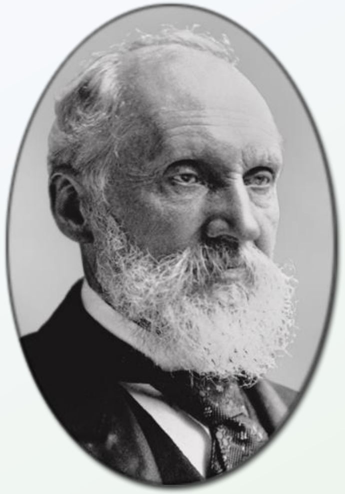


M.A. Abdu et al. / Journal of Atmospheric and Solar-Terrestrial Physics 67 (2005) 1643–1657

Measuring magnetic field



- 1833 – Carl Friedrich Gauss. First systematic study and measurement of the Earth’s magnetic field.
- Two basic types – vector and scalar magnetometers.
- Mechanical, electromagnetic, optical, quantum.
- Magnetic needle, Rotating coil, Induction coil, Fluxgate, Hall effect, Magnetoresistive; Proton, Overhauser, Optical pumping.

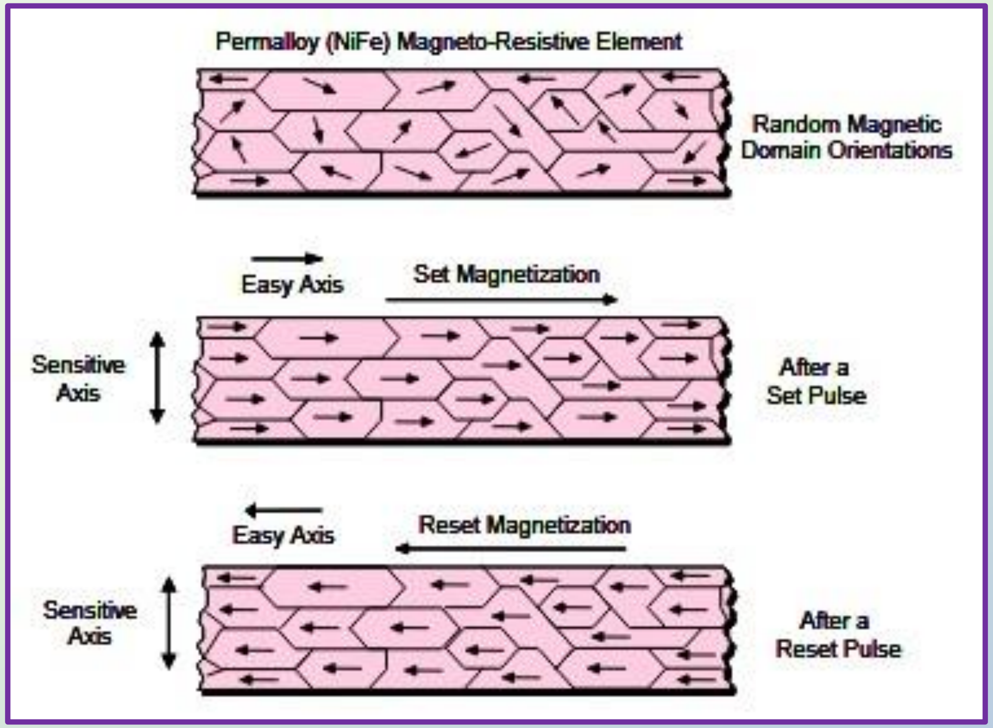


Magnetoresistance

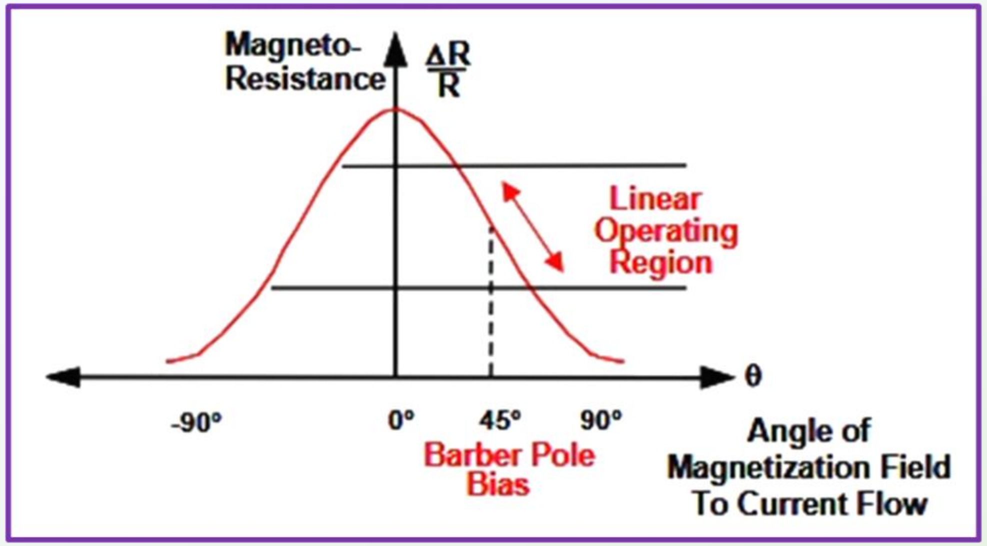
- 1856 - William Thomson (Lord Kelvin). “Dependence of electrical resistance on the angle between the direction of electric current and direction of magnetization.”
- Just to mansion: Giant magnetoresistance (**GMR**), Tunnel magnetoresistance (**TMR**), Colossal magnetoresistance (**CMR**), Extraordinary magnetoresistance (**EMR**), **Anisotropic magnetoresistance (AMR)**.

AMR Technology

- Permalloy (NiFe) thin-film crystalline ferromagnetic layer structure.
- Set/Reset function.

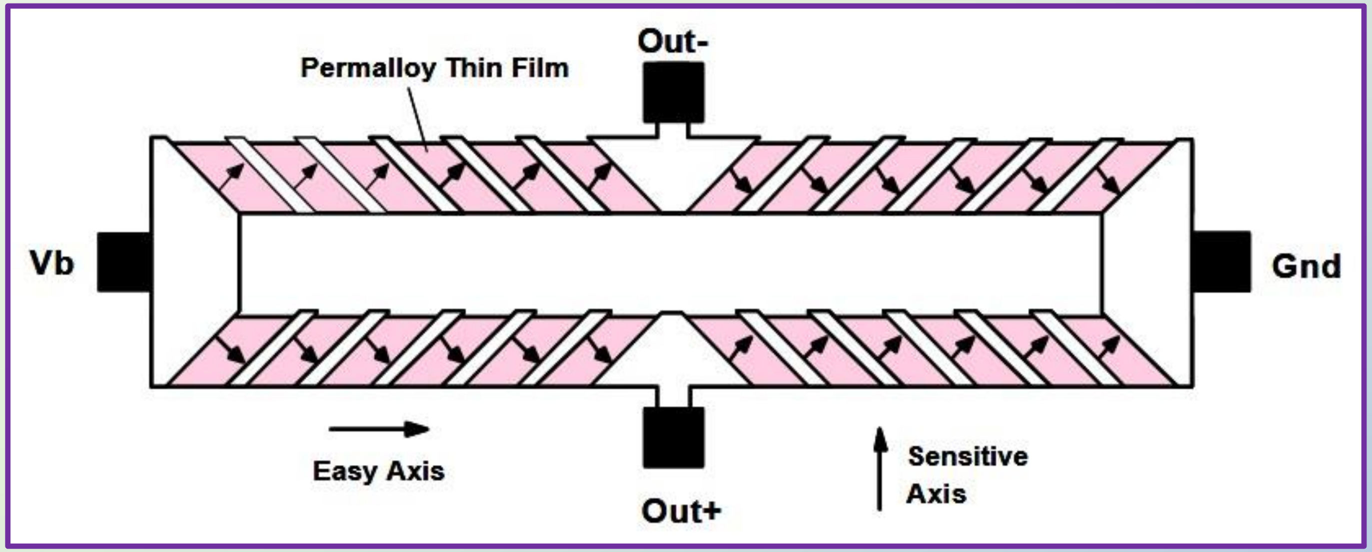


Honeywell International Inc. – www.magneticsensors.com



Honeywell International Inc. – www.magneticsensors.com

- Linear region of operation.
- Barber-pole configuration forming a Wheatstone bridge.



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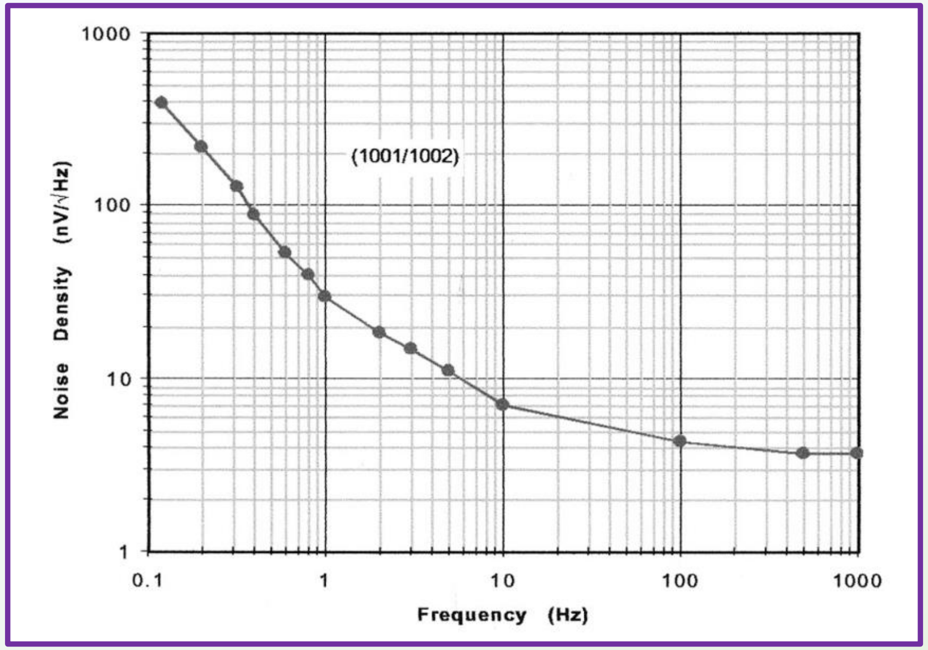
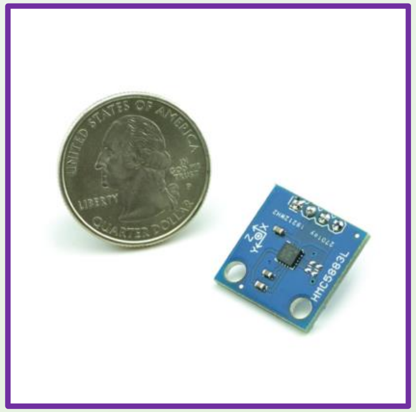
Why AMR?



HMC1001/1002 RMS noise spectral density curve.
Honeywell International Inc. – www.magneticsensors.com

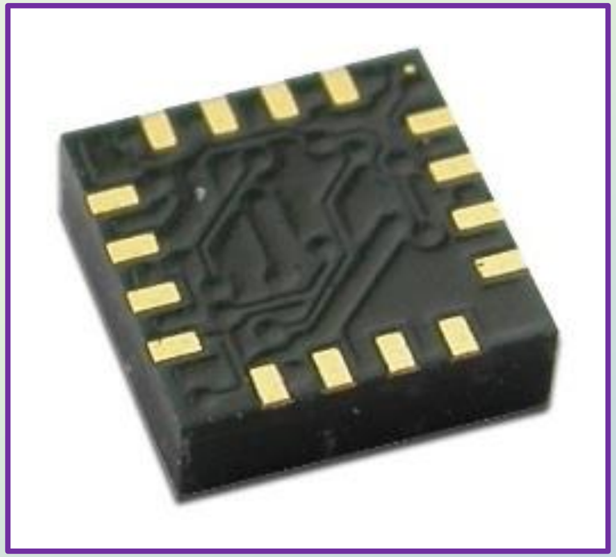


- The short answer is “Why not?”
- RMS noise spectral density at 1 kHz – 12 pT/Sqrt(Hz).
- Small energy demands!
- Miniaturization.
- Alternative to other technologies.

HMC5883L

(*Honeywell International Inc.*)

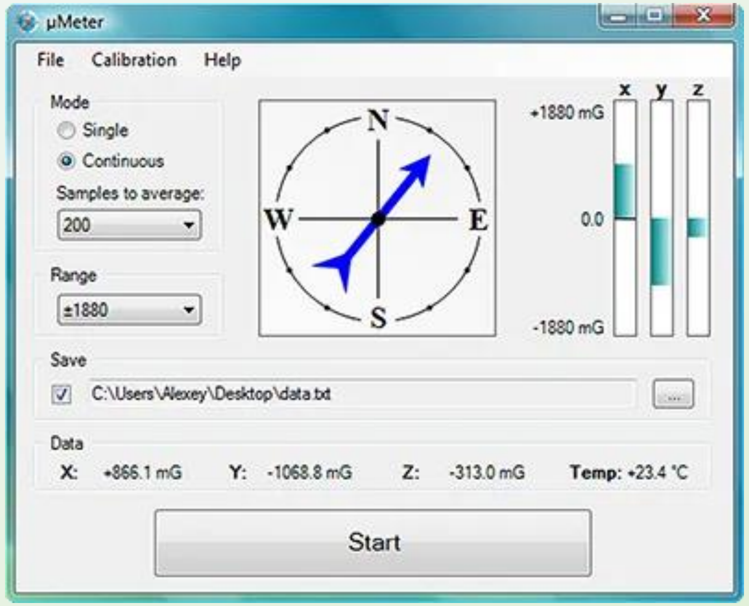
- 3-Axis Magnetoresistive Sensors in a tiny 3x3 mm SMD package.
- Built-in Set/Reset and Offset circuits.
- 12-Bit ADC.
- I^2C Digital Interface.
- Up to 160 Hz Output Rate.



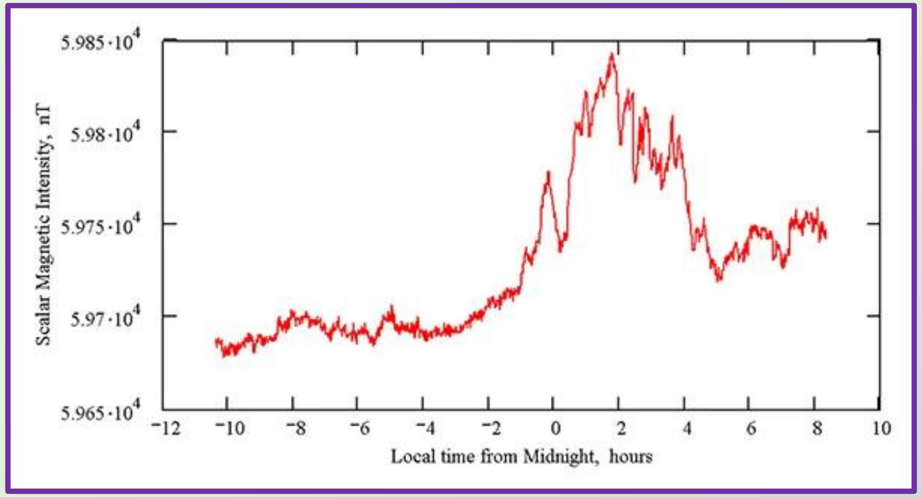
Honeywell International Inc.
www.magneticsensors.com

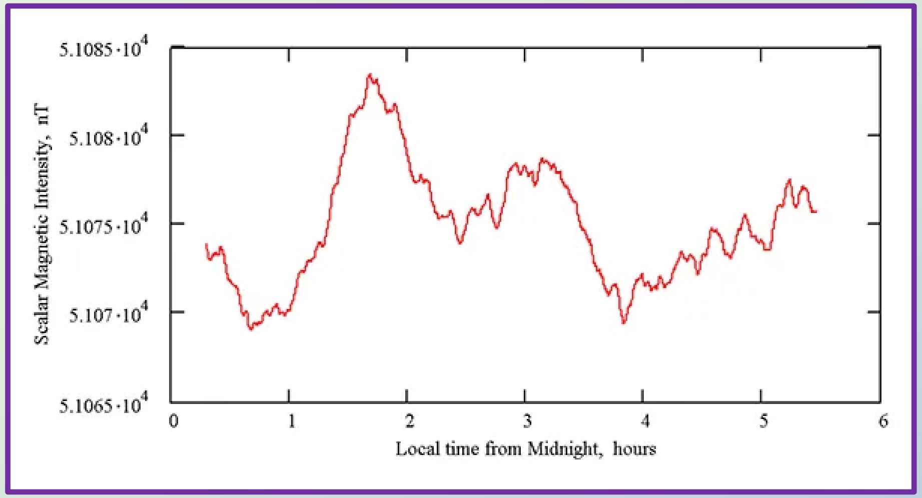
µMeter

Our first successful experience using AMR sensor technology.



November 06-07, 2012, Cairns, Australia
** Absolute values are not correct.*





March 20, 2013 in Stara Zagora, Bulgaria
** Absolute values are not correct.*

μMeter2

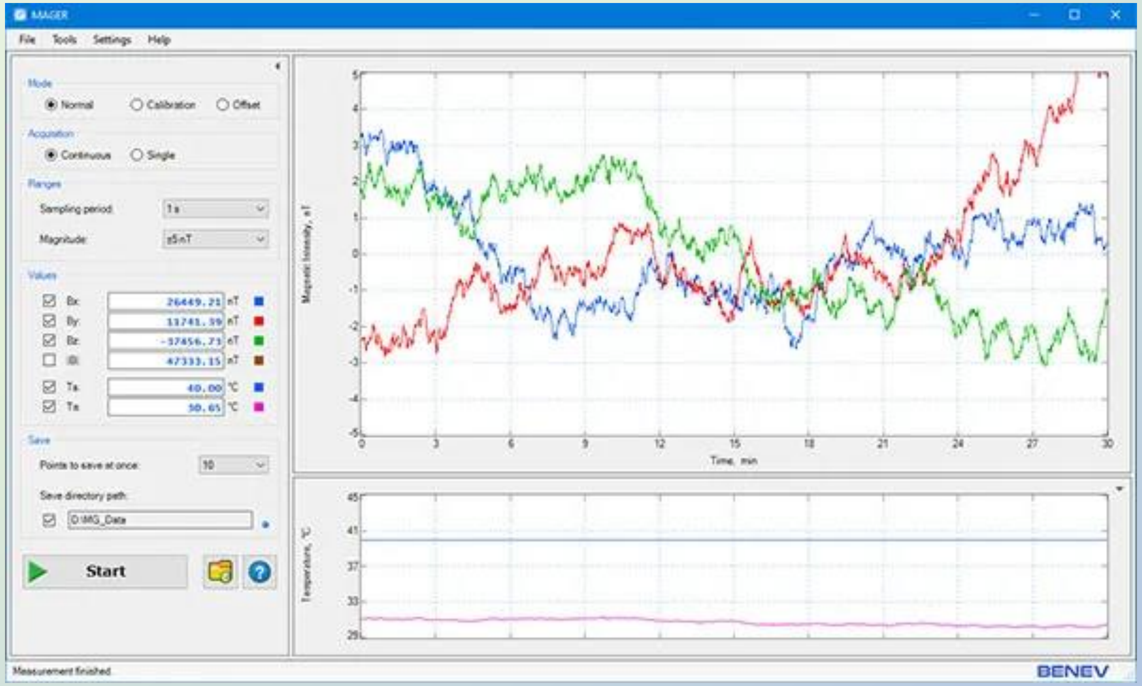
An improved version of μMeter magnetometer.

- Autonomous recording system.
- Multichannel AMR sensors.
- USB control.
- Independent battery-powered RTC.
- Internal SD memory card data storage.

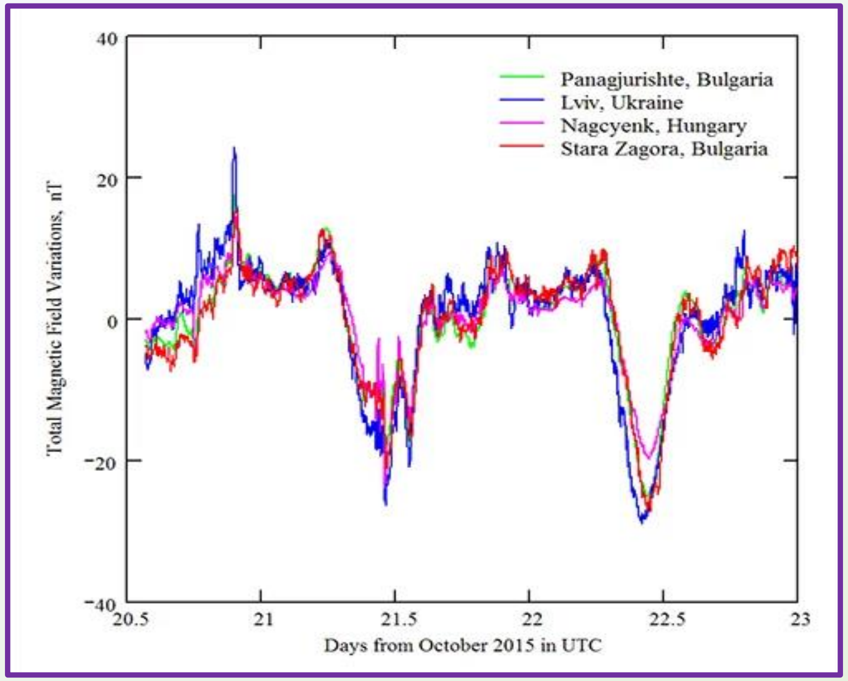
Cons: Strong temperature dependance of the measured data.

MAGER

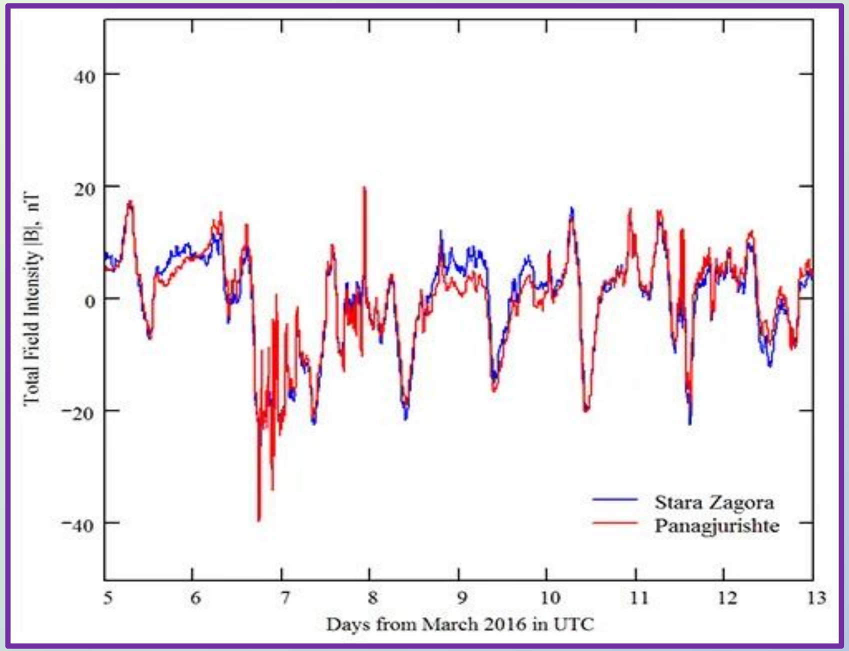
- Based on **HMC5883L.**
- Internal temperature stabilization on magnetic sensor triad.
- GUI Windows software with control over calibration process and temperature stabilization parameters.



MAGER - First data



Stara Zagora geomagnetic data and one-minute data from three INTERMAGNET geomagnetic observatories. Our data are filtered using a 5-minute low-pass bidirectional filter. The series covers the period from October 20-23, 2015.



Comparison of the total geomagnetic field intensity between Stara Zagora data and minute data from INTERMAGNET geomagnetic observatory in Panagjurishte (PAG), Bulgaria, covering the period March 05-12, 2016. The Stara Zagora data are filtered using a 15-minute low-pass bidirectional filter.

MG-01

Stating the task

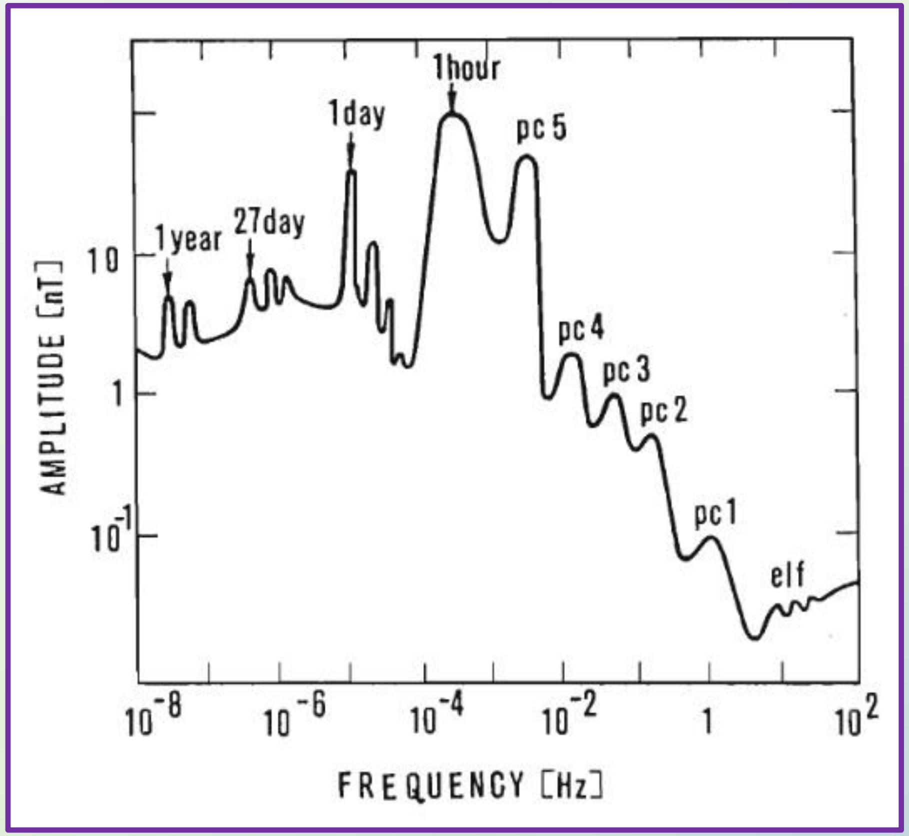
Some facts:

- Earth’s magnetic field ranges from 20000 nT in the equatorial zone to above 65000 nT near the magnetic poles. Magnetic storms are in the range from tens to hundreds of nT.
- According to IAGA: Continuous and Irregular (impulsive) magnetic pulsations.

Pulsation	Period (s)
Pc 1	0.2 to 5
Pc 2	5 to 10
Pc 3	10 to 45
Pc 4	45 to 150
Pc 5	150 to 600
Pc 6	Above 600

Pulsation	Period (s)
Pi 1	1 to 40
Pi 2	40 to 150
Pi 3	Above 150

Jankowski and Sucksdorff, 1996



Amplitudes of natural variations of the horizontal component of geomagnetic field.

Basic requirements:

- Geophysical and archeological surveys need accuracy better then 1 nT. Thus, we aim at least one order of magnitude better accuracy, SNR and temperature stability ~0.1 nT.
- Absolute accuracy ~1 nT after calibration procedure.
- Measuring range of ±70000 nT (10^5 / 10^{-1} = 10^6 – six orders of magnitude!).
- Sampling frequency from 10 Hz to DC.

Basic configuration

Utilizes ***HMC1001*** and ***HMC1002*** from *Honeywell International Inc.*

Two basic parts: Sensor Head (**SH**) and Interface Module (**IM**).

Sensor Head – nonmagnetic. Consists of measuring sensors, Set/Reset circuit, temperature stabilization block, precise low-noise analog electronics, ADC, MCU and connects to the **IM** through isolated digital interface.

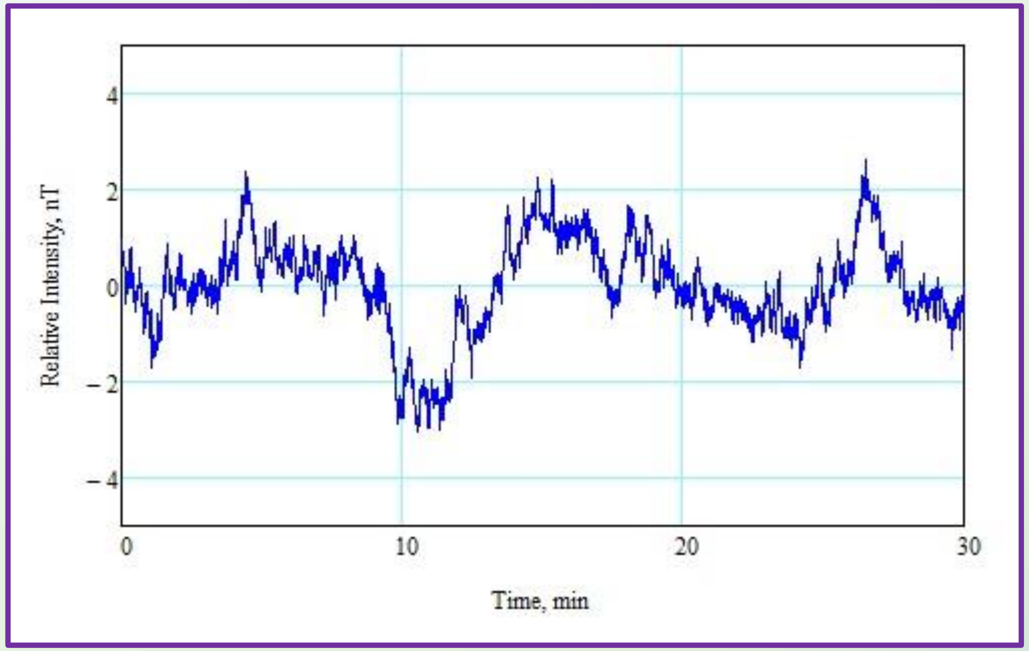
Interface Module supplies power to the **SH** and sends collected data to the PC through USB interface. It is implemented as USB HID device (no need of driver installation).

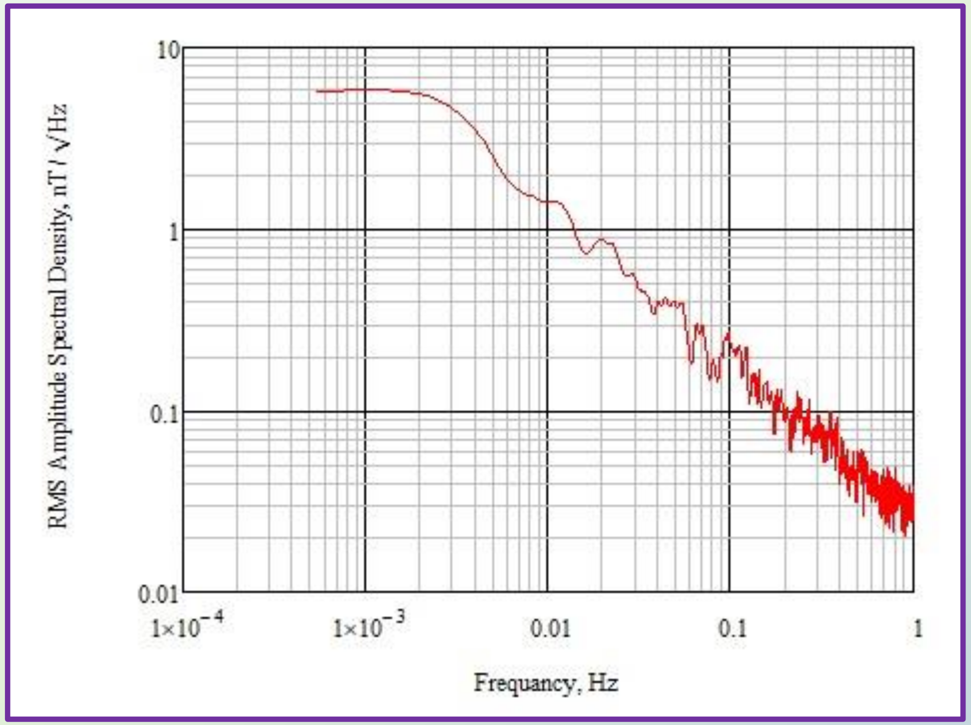
Working parameters

Parameter	Value
Range (on each axis)	±75000 nT
Bandwidth (-3 dB)	DC ÷ 20 Hz
Sensitivity @ 1 S/s	0.015 nT/ADU
Noise RMS spectral density @ 1 Hz	0.05 nT/Sqrt(Hz)
SNR @ 1 S/s	124 dB
ADC effective resolution @ 1 S/s	20.5 bit
Max sampling rate	10 S/s
Nominal power consumption	~1 W
Supply voltage	DC 12 ÷ 24 V
Weight (SH + IM)	360 g

Noise figure

So small values of noise are only possible in the magnetic noise-free environment, faraway from big urban structures.

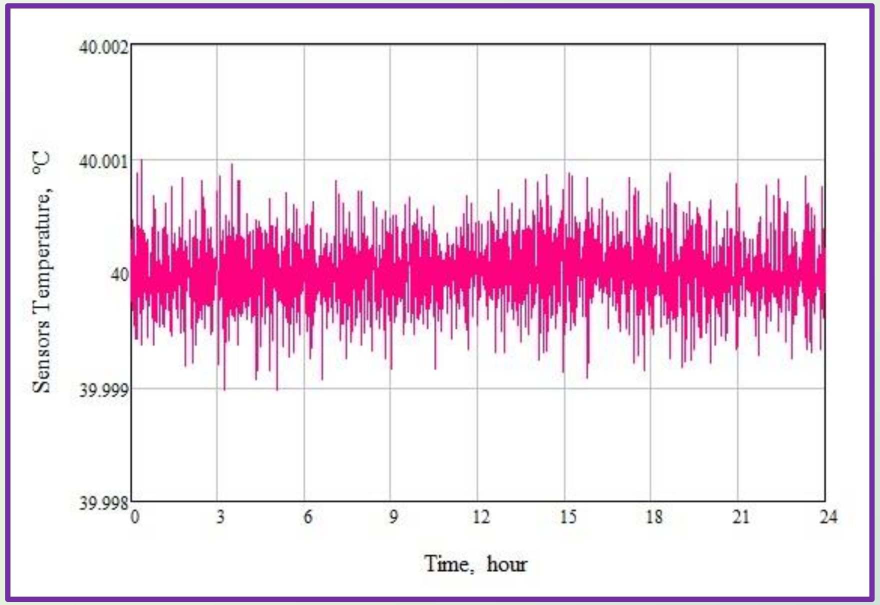




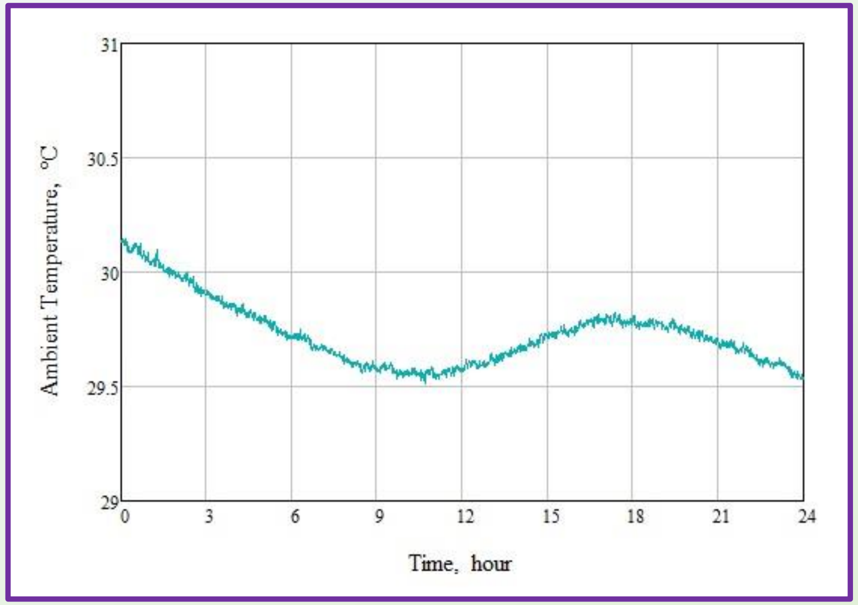
Temperature stabilization

- Small aluminum block with build-in heating element is mounted on the magnetic sensors triad.
- The block contacts with the sensor surface through thermo-conductive compound.
- Heating element is a set of nonmagnetic resistors switched on and off by a build-in PWM controller.
- The on board MCU controls the temperature implementing a PID algorithm. Magnetic measurements are taken during the off-state of the heating element.

The installation location must be chosen so that there are minimal daily fluctuations in the ambient temperature!



Sensor temperature fluctuations during 24 hours.



Ambient temperature variations during 24 hours.

Parameter	Value
Temperature accuracy @ 1 S/s (RMS)	0.003 °C
Temperature coefficient	0.35 nT/°C
Warm-up time	10 ÷ 15 min

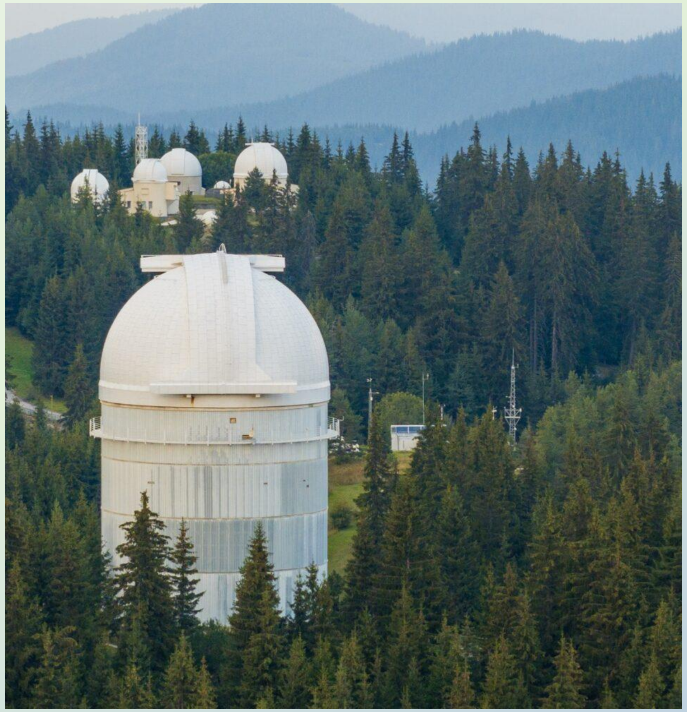
www.BenevSciTech.com

Installation

“IAGA Guide for Magnetic Measurements and Observatory Practice” by Jerzy Jankowski and Christian Sucksdorff.

A concrete shaft (without steel armature or any other ferromagnetic material) 1 m deep is poured out around a moisture protected plastic container. The shaft is buried in the ground on a shadow place in the nearby forest. The magnetometer is mounted on a wooden base lying on a stone bed on the bottom of the container. The shaft is covered by a thermo-isolated heavy ceramic plate. The closest buildings are about 100 m away.

This installation scheme ensures small enough fluctuations in the ambient temperature during the year.



NAO – Rozhen
41°41’36”N 24°44’20”E
1759 m

Calibration - Theory

Definitions:

"Comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy". *(Wikipedia)*

"Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties (of the calibrated instrument or secondary standard) and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication". *(BIPM)*

“Finding the relation, to some degree of well-defined accuracy, between DUT output data and physical quantity”. (BB)

“Complete Triaxis Magnetometer Calibration in the Magnetic Domain” by Valérie Renaudin et al. (Journal of Sensors, 2010).

“New Method for Magnetometers Based Orientation Estimation” by Valérie Renaudin et al. (IEEE/ION PLANS, 2010).

(Why symmetrical matrix?)

Magnetometer error model:

1. Instrumentation errors.
   - Scale factor – 3x3 square diagonal matrix $\boldsymbol{S}$.
   - Nonorthogonality and misalignment – 3x3 matrix $\boldsymbol{M}$.
   - Sensor offset – 3x1 vector $\boldsymbol{b}_{so}$.
2. Magnetic deviation.
   - Hard iron – 3x1 vector $\boldsymbol{b}_{hi}$.
   - Soft iron – 3x3 matrix $\boldsymbol{A}_{si}$.
3. Random gaussian noise $\boldsymbol{\varepsilon} \sim N(0, \sigma_{\varepsilon}^2)$.

Let ***h*** represents error-free magnetic field and $\hat{\boldsymbol{h}}$ *represents sensor triad readings. Then*

$$\hat{h} = S * M * (A_{si} * h + b_{hi}) + b_{so} + \varepsilon$$

Using combined 3x3 square matrix $A = S * M * A_{si}$ and 3x1 vector $b = S * M * b_{hi} + b_{so}$, this represents a linear error model:

$$\hat{h} = A * h + b + \varepsilon \Rightarrow h = A^{-1} * (\hat{h} - b - \varepsilon)$$

Our goal is to find A^{-1} *and* ***b*** (12 unknown parameters).

Few aproaches are possible to the calibration procedure:

- Using theoretical model of the Earth’s magnetic field, e.g. IGRF model.
- Using another calibrated magnetometer as an *in-situ* secondary standard.
- Using a Helmholz coil system. (https://benevscitech.com/en/coil-systems-magnetometers-calibration.html)
- Using the absolute magnitude value of the local geomagnetic field with the reference to one of the nearby INTERMAGNET magnetic observatories.

Magnetic observatory in Panagyurishte (PAG), part of the INTERMAGNET network, as a reference point!

Rotating the magnetometer in 3D space:

- $\boldsymbol{h}$ describes a sphere $\boldsymbol{S_{Local}}$ with radius $\boldsymbol{H_{PAG}}$.
- $\boldsymbol{\hat{h}}$ describes an ellipsoid $\boldsymbol{E_{Local}}$ *(guaranteed by the linear error model).*

Two-stage calibration process.

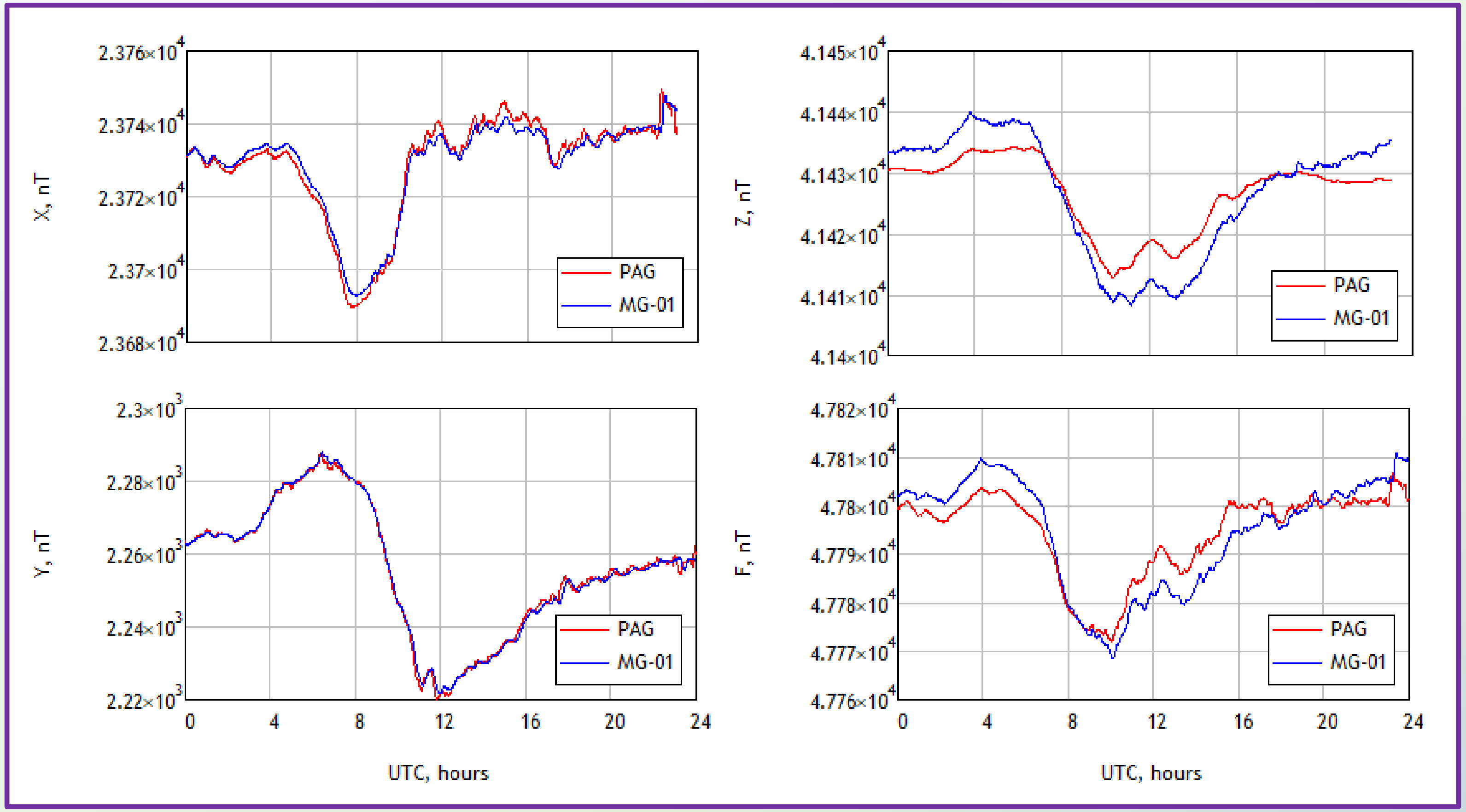
- Find the Transform $\boldsymbol{E_{Local}}$ **–>** $\boldsymbol{S_{Local}}$.
- Find the Rotation $\boldsymbol{S_{Local}}$ **–>** $\boldsymbol{S_{PAG}}$.

Calibration steps:

1. Rotating the magnetometer only in a small vicinity in 3D space around installation mounting point (±5 degrees at each Euler angle), thus ensuring strict linearity. Sampling period is 0.5 s or 1 s.
2. Using **Levenberg-Marquardt** optimization algorithm to find combined $\boldsymbol{A^{-1}}$ and $\boldsymbol{b}$. Thus, transforming the ellipsoid $\boldsymbol{E_{Local}}$ into a sphere $\boldsymbol{S_{Local}}$ with origin at ***P(0,0,0)*** and radius $\boldsymbol{H_{PAG}}$.
3. Using INTERMAGNET (PAG) observational data and **Levenberg-Marquardt** algorithm or **Kabsch** algorithm (**Wahba** problem) to find the rotation transform $\boldsymbol{S_{Local} \rightarrow S_{PAG}}$.

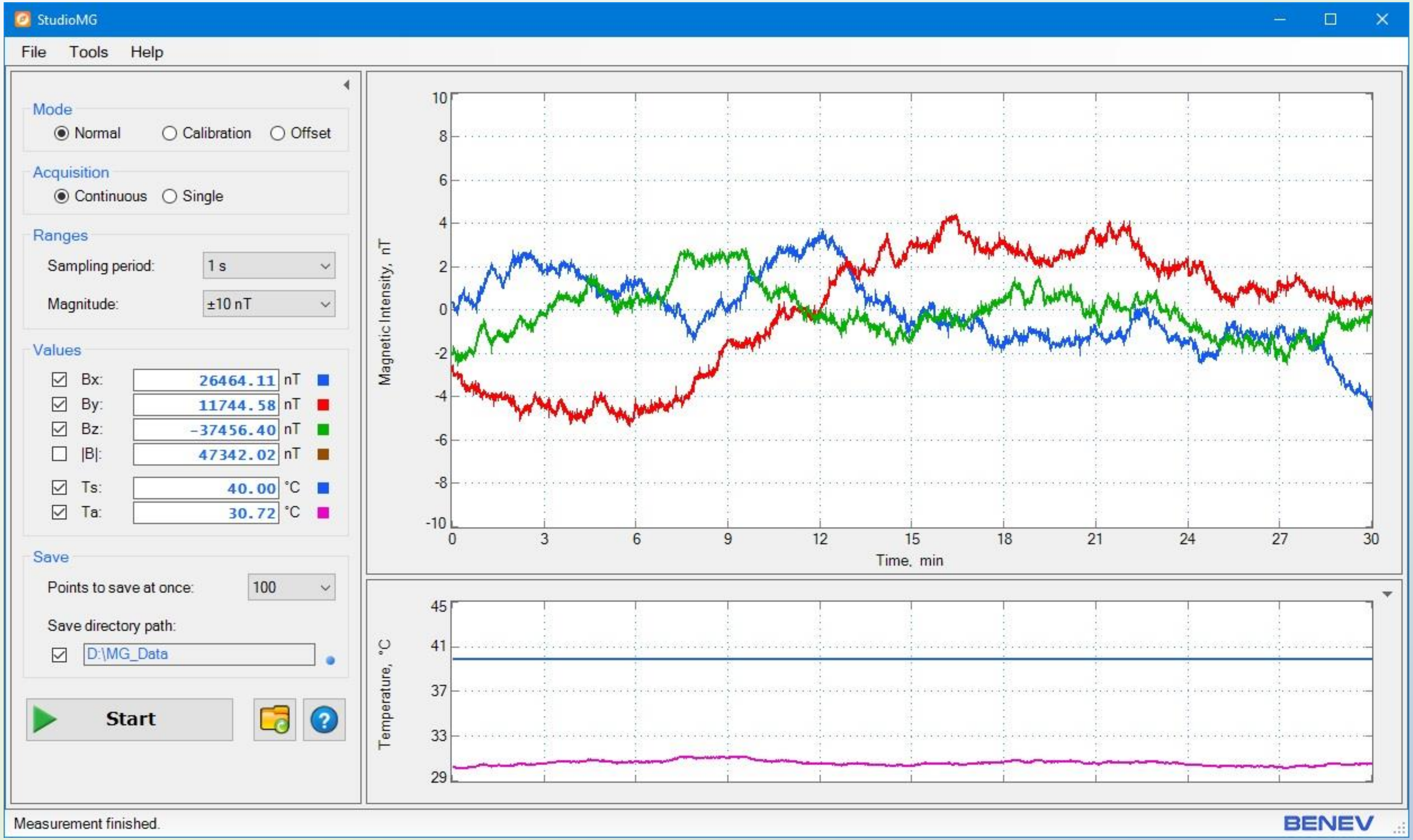
Whole calibration procedure takes only a few minutes!

Calibration - Results



Earth's magnetic field components comparison between PAG and MG-01 minute data after magnetometer calibration procedure. Data shown here depict daily geomagnetic variations on 31 August, 2025. The RMS deviations are: σX = 2.43 nT; σY = 1.11 nT; σZ = 4.20 nT; σF = 4.42 nT .

StudioMG (v1)


StudioMG
File
Tools
Help
Mode
Normal
Calibration
Offset
Acquisition
Continuous
Single
Ranges
Sampling period:
1 s
Magnitude:
±10 nT
Values
Bx:
26464.11
nT
By:
11744.58
nT
Bz:
-37456.40
nT
|B|:
47342.02
nT
Ts:
40.00
°C
Ta:
30.72
°C
Save
Points to save at once:
100
Save directory path:
D:\MG_Data
Start
Magnetic Intensity, nT
Time, min
Temperature, °C
Measurement finished.
BENEV

StudioMG (v2)


Open file
Sampling
Calibration
PID
Settings
START
MAGNETIC INTENSITY - X
MAGNETIC INTENSITY - Y
MAGNETIC INTENSITY - Z
MAGNETIC INTENSITY - F
Intensity, nT
UTC, hours
23150
23145
23140
23135
11730
11728
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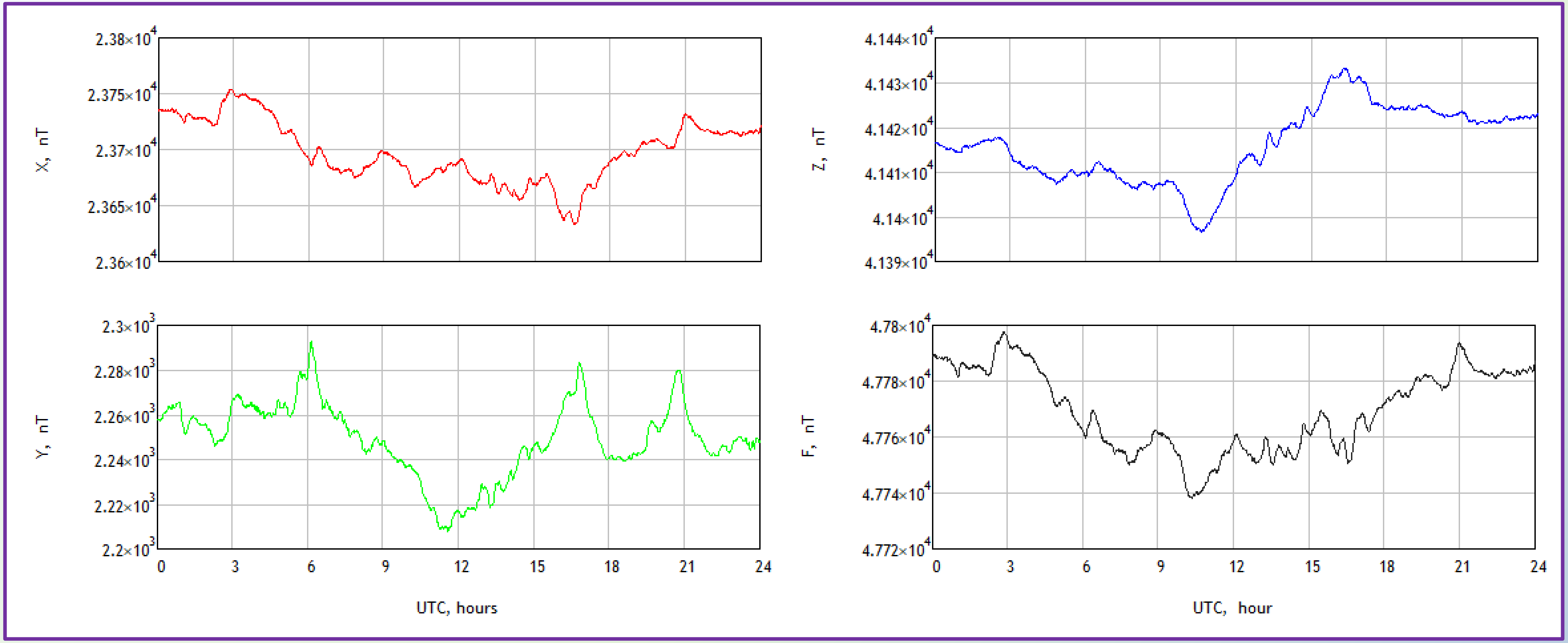
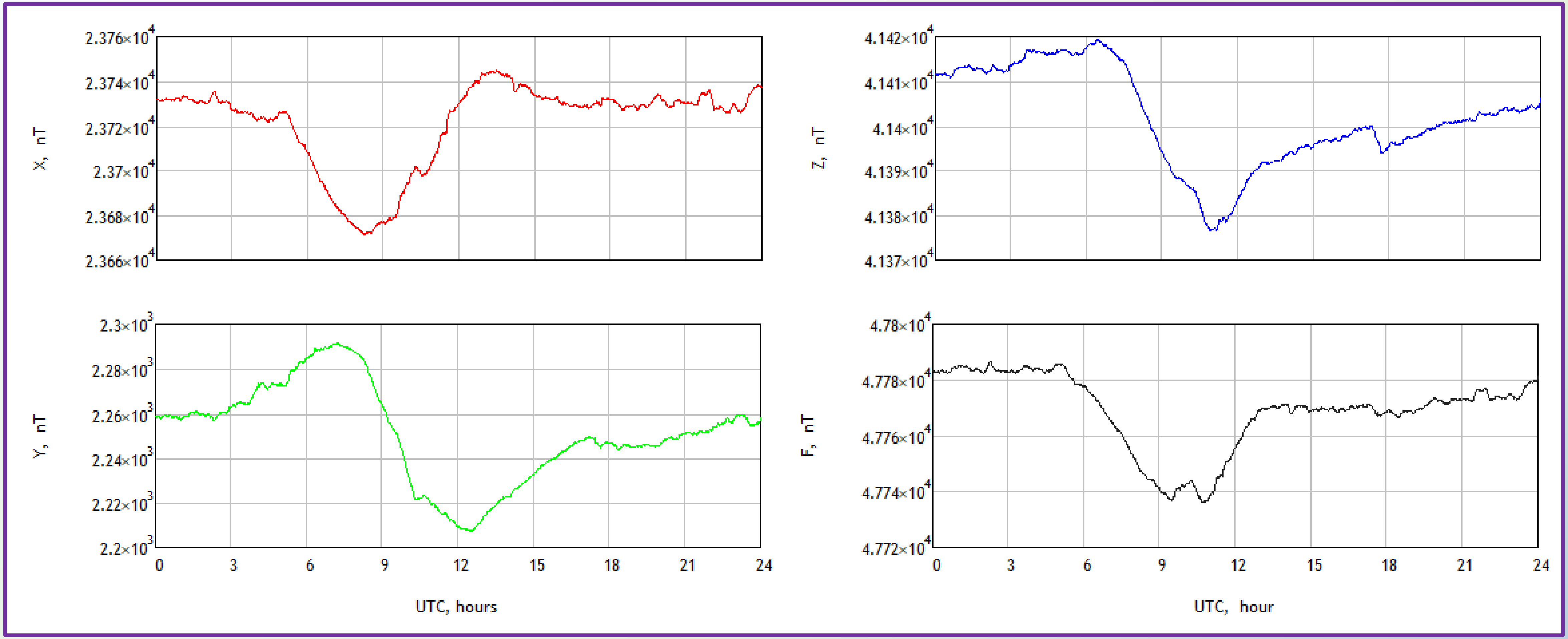
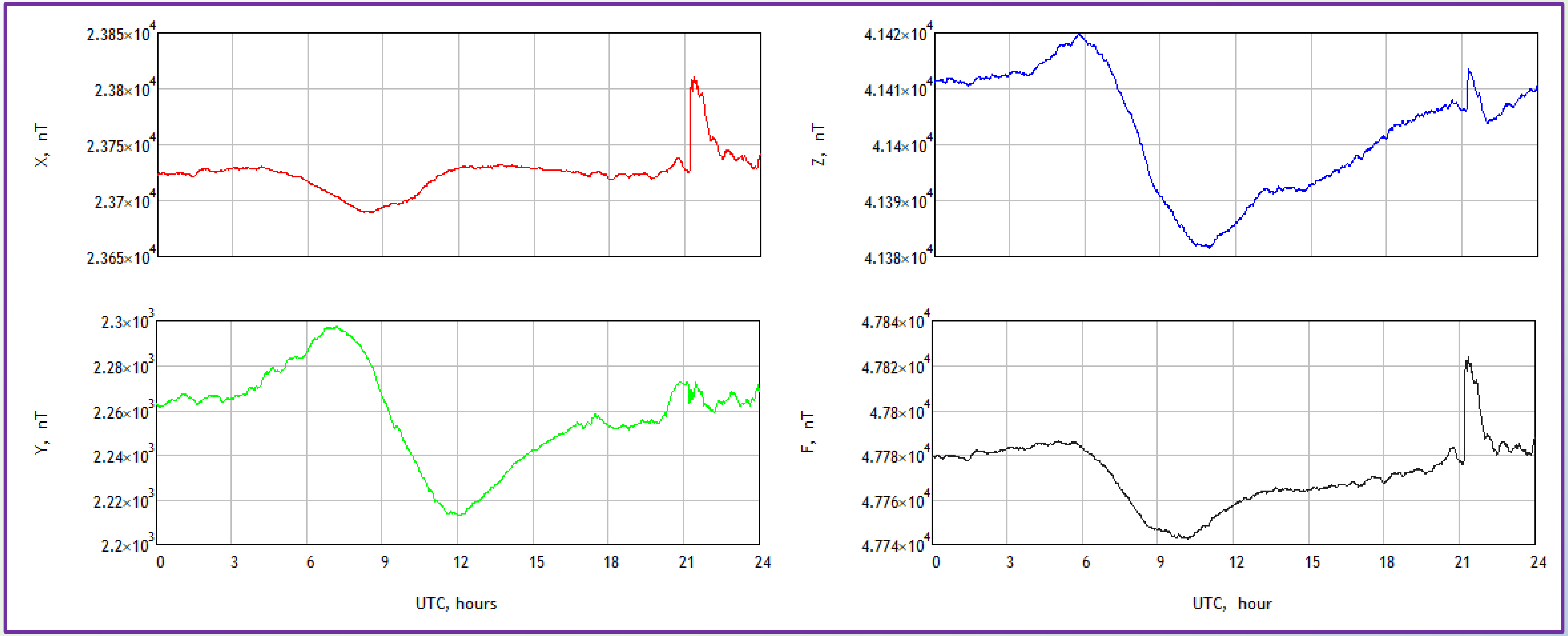
Observational data



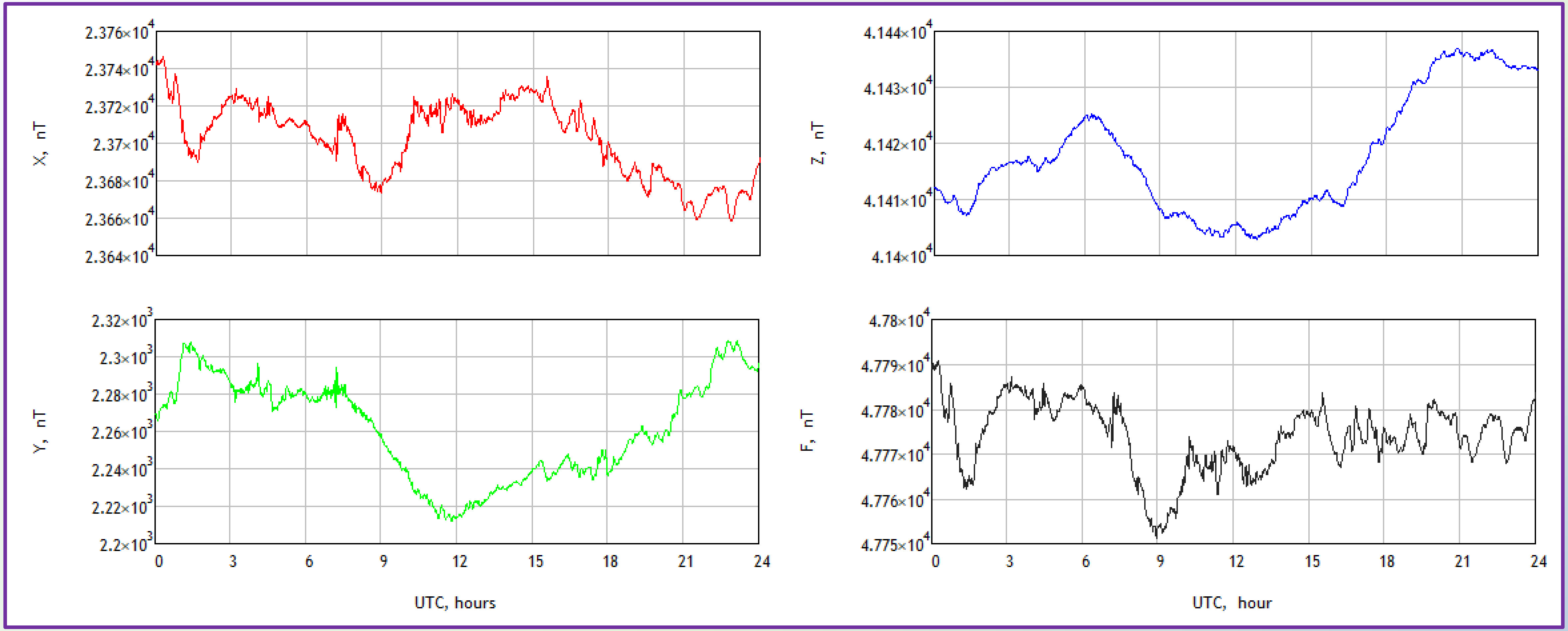
09 August, 2025. Slight magnetic perturbations are observed.



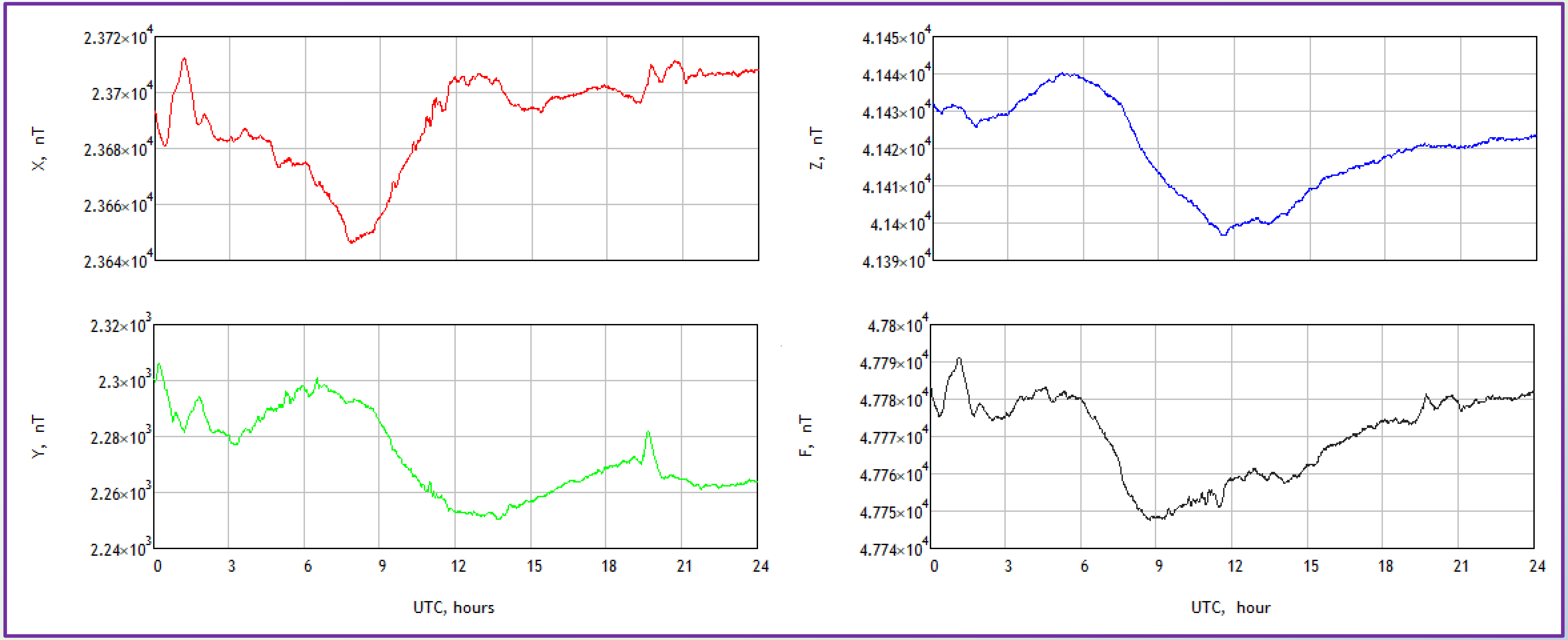
26 August, 2025. Quiet day with almost no perturbations.



01 September, 2025. Magnetic perturbations start at 21:00 UTC.



02 September, 2025. Evolution of the magnetic storm started on 01 September, 2025 at 21:00 UTC during the next 24 hours.



03 September, 2025. Magnetic perturbations decrease in amplitude.

Ideas and Perspectives to the Future

- RS-485 communication between SH and IM.
- New software with fully automatic operation of recording raw data and filtered minute data.
- Real-time online data archive with minute data in IAGA2002 INTERMAGNET Exchange Format and ImagCDF (NASA's Common Data Format).
- **NAO Rozhen** as part of INTERMAGNET.

- Ring network (SATI).
- Multi observational points network.
- Satellite missions.
- Drone (geophysical and archeological surveys).
- Joint projects with **Bulgarian Academy of Sciences** and other research organizations.

BOSA-02, BOSA-04

Automotive Diagnostic Oscilloscopes

GTR-01

Quantum Hardware Random Number Generator

- Avalanche noise in the reverse-biased p-n junction as an entropy source.
- Data output rate through a USB interface up to 2.2 Mb/s.
- 12-bit precise calibration with EEPROM values storage.
- Statistical validation using ***NIST STS, TestU01, Diehard!***

Thank You For Your Attention!

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