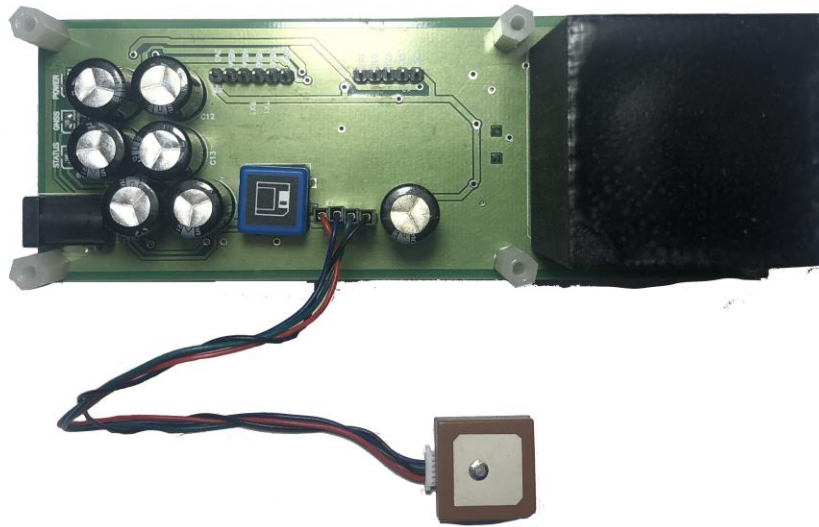


**FG-43**  
**3-AXIS FLUXGATE MAGNETOMETER SYSTEM**  
**Datasheet and user manual V1**



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## 1. Features and technical data

Features:

- 0.1 nT sensitivity per each axis with up to 33 Hz sample rate;
- GPS and automatic SD card data logger with USB mass storage interface inside;
- Compact, light, precise and easy to use.

Applications: precision flight/marine magnetometer/compass, archeology/geology magnetometer with GPS and automatic SD card data logger;

Technical data

| Parameter                              | MIN      | TYP | MAX  | Units |
|--|----------|-----|------|-------|
| Power supply requirements              |          |     |      |       |
| Supply voltage range                   | 7        | 12  | 16   | V     |
| Supply current (from 8V to 12V supply) | 110      | 120 | 147  | mA    |
| Measurements                           |          |     |      |       |
| Magnetic field sensor sensitivity      |          | 0.1 |      | nT    |
| Magnetic field range per each axis     | +/-80000 |     |      | nT    |
| Temperature sensor sensitivity         |          | 0.1 |      | °C    |
| Temperature measurement range          | -40      |     | +125 | °C    |
| USART data output rate                 |          |     |      |       |
| – serial capture mode                  | 2        | 3   | 4    | Hz    |
| – simultaneous capture mode            | 28       | 33  | 39   |       |
| Data to uSD card rate                  |          |     |      |       |
| – serial capture mode                  | 2        | 3   | 4    | Hz    |
| – simultaneous capture mode            | 28       | 33  | 39   |       |
| uSD card capacity                      |          |     | 8    | GB    |
| Mechanical & Environment               |          |     |      |       |
| Length                                 |          | 135 |      | mm    |
| Width                                  |          | 48  |      |       |
| Height                                 |          | 50  |      |       |
| Weight                                 |          | 122 |      | g     |
| Environment temperature range          | -20      |     | +50  | °C    |

## 2. Overview

A simple 3-axis fluxgate magnetometer system consists of 3x orthogonal FG-4 fluxgate sensors connected to processor board based on powerful STM32F401 MCU.

Magnetometer has USART interface only to communicate with external devices, e.g. MCU, PC, Arduino, Raspberry boards, etc.

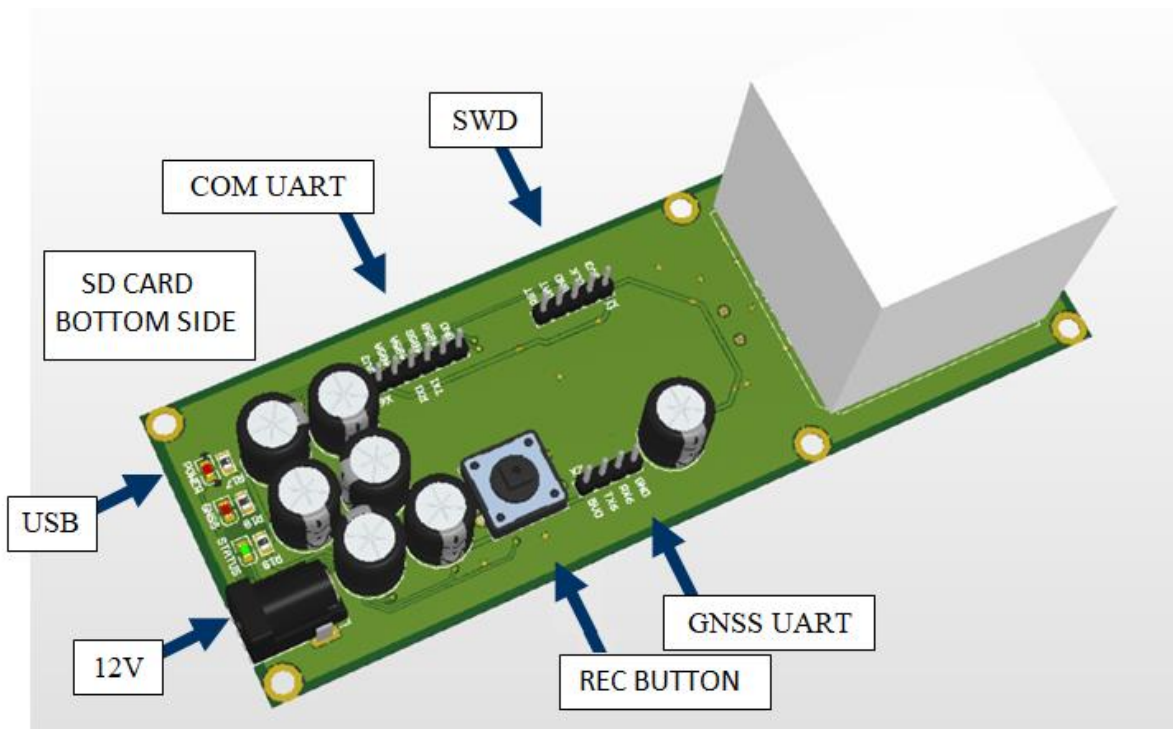


Fig.2-1. FG-43 design

USB port is used to download data from SD card only. Under board is place for micro SD card for data recording. Next to USB is jack for power supply sensor. Between USB and 12V jack there are 3. Status LED. 1. Green POWER, 2. Yellow GNSS, 3. Red STATUS

Note: when you want to download data from SD card there is no need to power sensor. It will be supplied from USB cable.

In addition to USART interface, has the following built-in features:

- GPS module is connected to STM32F401 MCU by second USART interface. GPS antenna placed right under magnetic field sensor axis diagram on the top side of enclosure;
- microSD card holder (**Card not included!**) connected to STM32F401 MCU by SDIO interface;
- USB Mass Storage Class interface in order to connect to PC as convenient capacity flash disk without another special software or driver requirement;
- status LEDs

### 3. Pinout and connection diagrams.

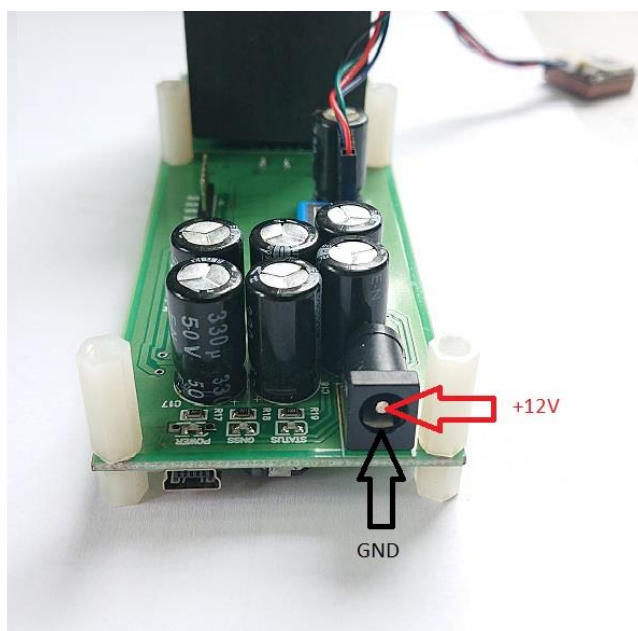


Fig.3-1. 12V power supply  
Barrel plug 5.5mm (Plug +12V, barrel GND)

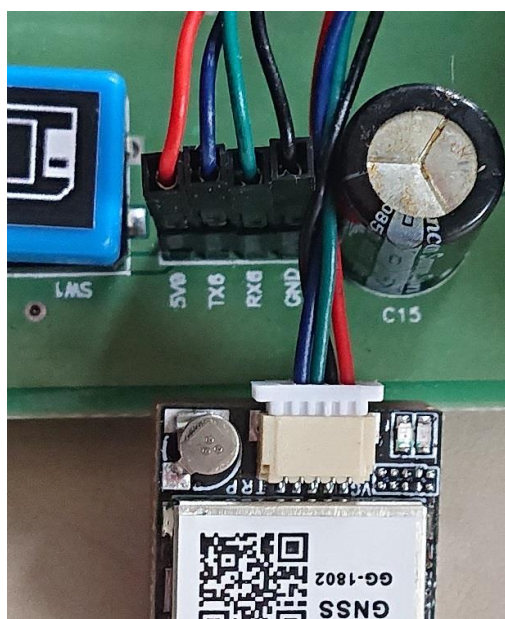


Fig.3-2. GPS connector  
1. 5V0-red, 2. TX6-blue, 3. RX6-green, 4. GND-black

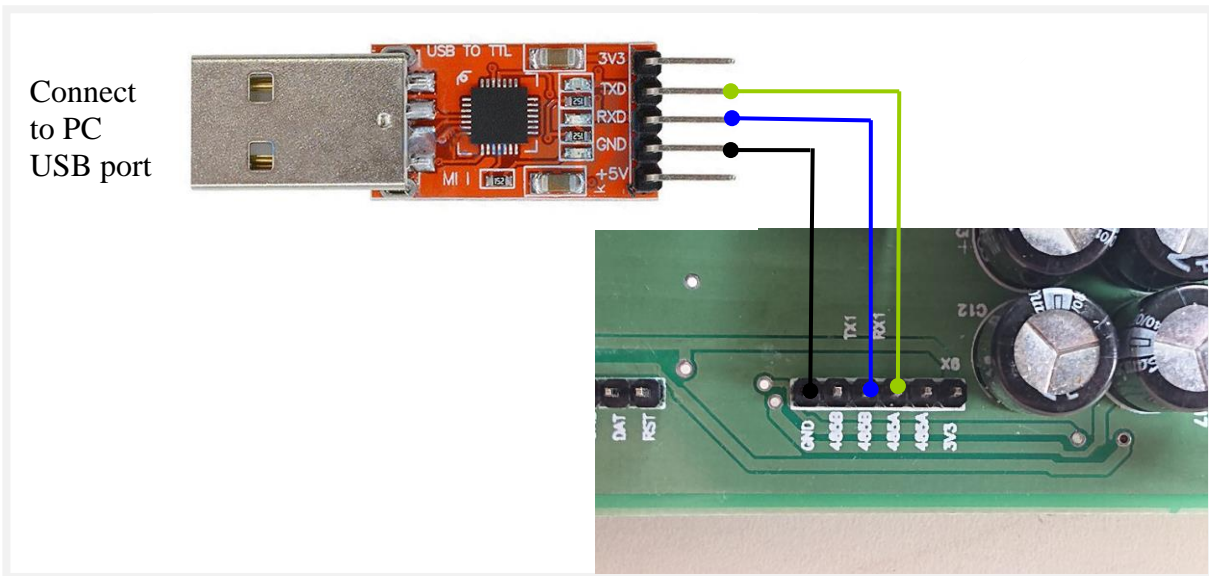
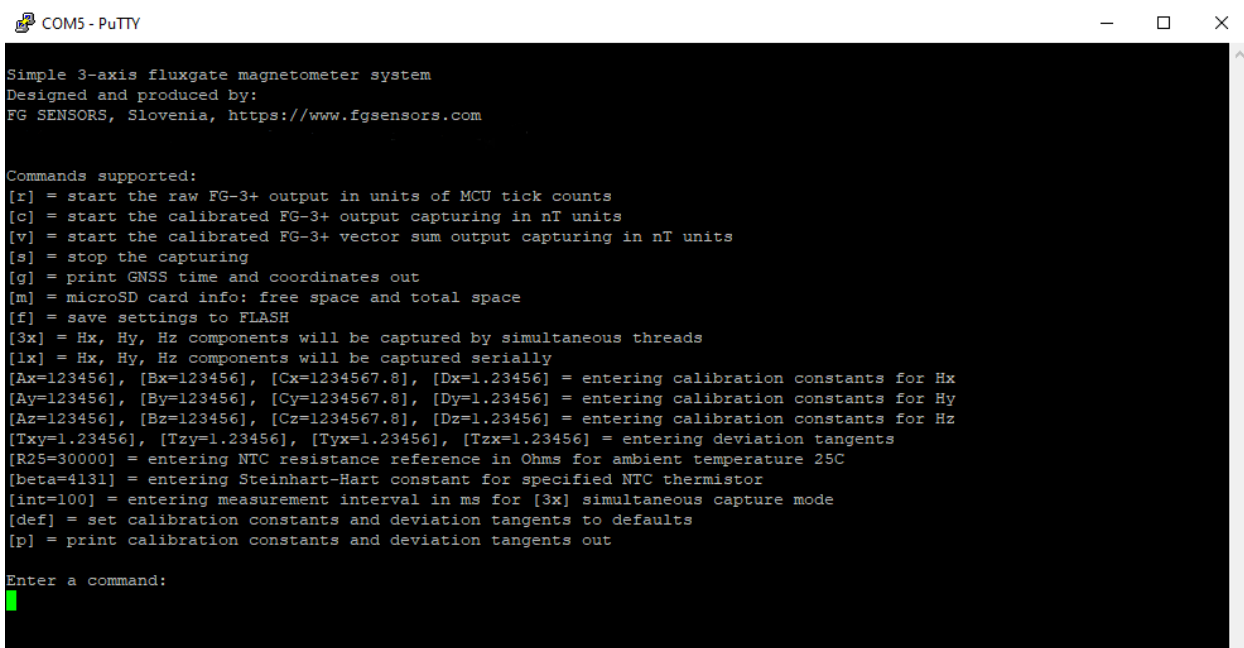


Fig.3-3. Example diagram of PC connection

**Connecting to PC according to fig.3-3 follow carefully the sequence of steps below**

- 3.1. Put on power supply to magnetometer;
- 3.2. Connect USB to TTL board to magnetometer as shown in the fig.3-3 by black, blue and green wires;
- 3.3. Connect USB to TTL to PC, open specified COM port in terminal with baud rate 115200 bps;
- 3.6. Put any character into terminal window.

## 4. USART command system



```
COM5 - PuTTY
Simple 3-axis fluxgate magnetometer system
Designed and produced by:
FG SENSORS, Slovenia, https://www.fgsensors.com

Commands supported:
[r] = start the raw FG-3+ output in units of MCU tick counts
[c] = start the calibrated FG-3+ output capturing in nT units
[v] = start the calibrated FG-3+ vector sum output capturing in nT units
[s] = stop the capturing
[g] = print GNSS time and coordinates out
[m] = microSD card info: free space and total space
[f] = save settings to FLASH
[3x] = Hx, Hy, Hz components will be captured by simultaneous threads
[1x] = Hx, Hy, Hz components will be captured serially
[Ax=123456], [Bx=123456], [Cx=1234567.8], [Dx=1.23456] = entering calibration constants for Hx
[Ay=123456], [By=123456], [Cy=1234567.8], [Dy=1.23456] = entering calibration constants for Hy
[Az=123456], [Bz=123456], [Cz=1234567.8], [Dz=1.23456] = entering calibration constants for Hz
[Txy=1.23456], [Tzy=1.23456], [Tyx=1.23456], [Tzx=1.23456] = entering deviation tangents
[R25=30000] = entering NTC resistance reference in Ohms for ambient temperature 25C
[beta=4131] = entering Steinhart-Hart constant for specified NTC thermistor
[int=100] = entering measurement interval in ms for [3x] simultaneous capture mode
[def] = set calibration constants and deviation tangents to defaults
[p] = print calibration constants and deviation tangents out

Enter a command:
```

Fig.4-1. Simple 3-axis fluxgate magnetometer command reference in terminal window

Command is a char or sequence of chars sent to simple 3-axis fluxgate magnetometer system at once via USART. Commands can be received from PC if connections provided as shown in the fig.3-3.

The following communication settings are required: 115200 bps, 8 bit word length, 1 stop bit, no parity and no flow control required.

The following commands are supported.

**4.1. Command «r»** starts the raw magnetic field measurements output in units of built-in MCU tick counts (see «The input capture» in p.27 of AN4667 rev.3 «General-purpose timer cookbook for STM32 microcontrollers»).

Answer generated by following instruction each time when capture completed:

```
sprintf(USART1txString, "Tx=%d; Ty=%d; Tz=%d; t=%d;\n\r", Tx, Ty, Tz, t_adc_code);
```

where *Tx* is period captured from x-sensor, *Ty* is period captured from y-sensor, *Tz* is period captured from z-sensor, *t\_adc\_code* is adc code of voltage measured on NCP18WB333 temperature sensor.

**4.2. Command «c»** starts the calibrated magnetic field measurements output with 0.1 nT resolution. Answer generated by following instruction each time when capture completed:

```
sprintf(USART1txString, "Hx=%f; Hy=%f; Hz=%f; t=%f;\n\r", Hx, Hy, Hz, temperature);
```

where *Hx*, *Hy*, *Hz*, *temperature* are magnetic field components and temperature measured respectively.

**4.3. Command «v»** starts the vector sum output with 0.1 nT resolution. Answer generated by following instruction each time when capture completed:

```
sprintf(UART1txString, "H=%f; t=%f;\n\r", H, temperature);
```

where  $H = Hypot(Hx, Hy, Hz)$  is vector sum of magnetic field components.

**4.4. Command «s»** stops the capture output. If any char or sequence not supported will be sent, the capture output will be stopped, but command reference will be received from magnetometer system as the answer. Sending the command «s» cause no answer need received from magnetometer system;

**4.5. Command «g»** show date, time and GPS location;

**4.6. Command «m»** micro-SD data. Total and available space on your SD card;

**4.7. Command «f»** save the current capture mode, interval of capture and calibration constants to internal FLASH in order to set them again at next launch of magnetometer system;

**4.8. Command «3x»** switches on all sensors to keep active state for simultaneously capturing the output. This is the fastest way to capture the measurements produced up to 20 3-axial measurements per second. However, each active sensor produces magnetic field, which causes other sensors output;

**4.9. Command «1x»** switch sensors to be captured sequentially in order to avoid magnetic fields interaction. Each time only 1 sensor active, other 2 sensors powered off. Only 3 measurements per second provided in this mode.

#### **4.10. Commands to entering calibrating constants**

Because FG-4 sensor usually provide not linear output, the calibrated curve should be approximated by high-order function (see examples in section 6). A combined tangent function found as good balance between precision, calculation speed and easy calibration:

$$Hx = Ax + Bx * \tan(Cx/Tx + Dx);$$

$$Hy = Ay + By * \tan(Cy/Ty + Dy);$$

$$Hz = Az + Bz * \tan(Cz/Tz + Dz);$$

where  $Tx, Ty, Tz$  are captured periods in units of MCU ticks,  $Axyz, Bxyz, Cxyz, Dxyz$  are calibrated constants.

Because each FG-4 sensor has unique shape of output function  $H(T)$ , the calibrated constants have different values as default.

Please take look calibration document how to do calibration on your home if needed.

#### **4.11. Commands to set deviation tangents**



Deviation tangents are tangents of angles fluxgate sensors axes are deviated from ideal orthogonal directions. It is known how difficult to install fluxgate sensors ideally on 90° from each other in the practice: every time even some small deviation occurred.

Sensor axes deviations produce an error when module of magnetic strength vector  $H$  calculated from  $H_x$ ,  $H_y$  and  $H_z$  components measured. We can eliminate this error using simple mathematic technique described in section 6.

Let z-axis be always true, then actual values of  $H_x$ ,  $H_y$  and  $H_z$  calculated from measured ones  $H_x^*$ ,  $H_y^*$  and  $H_z^*$  using following expressions:

$$H_x = \frac{-H_x^* \cdot \sqrt{1 + t_{yx}^2 + t_{zx}^2} + H_y^* \cdot t_{yx} \cdot \sqrt{1 + t_{xy}^2 + t_{zy}^2} + H_z^* \cdot (t_{zx} - t_{zy} \cdot t_{yx})}{t_{xy} \cdot t_{yx} - 1}$$

$$H_y = \frac{H_x^* \cdot t_{xy} \cdot \sqrt{1 + t_{yx}^2 + t_{zx}^2} - H_y^* \cdot \sqrt{1 + t_{xy}^2 + t_{zy}^2} + H_z^* \cdot (t_{zy} - t_{zx} \cdot t_{xy})}{t_{xy} \cdot t_{yx} - 1} ;$$

$$H_z = H_z^*$$

where:

$t_{xy}$  and  $t_{zy}$  – are tangents of angles between  $H_y^*$  vector projections to  $xy$  and  $yz$  planes;  
 $t_{yx}$  and  $t_{zx}$  – are tangents of angles between  $H_x^*$  vector projections to  $xy$  and  $xz$  planes.

#### 4.12. Commands to calibrate the temperature sensor

To measure the temperature the NTC thermistor placed on the PCB. Because of NTC sensor usually provide not linear resistance output, the temperature should be calculated from simplified Steinhart – Hart equation:

$$R_{NTC}/R_{25} = \exp(B/(t+273) - 1/298);$$

where  $R_{NTC}$  is resistance of NTC sensor measured by MCU at given temperature  $t^\circ\text{C}$  ( $t+273\text{K}$ ),  $R_{25}$  is resistance at  $25^\circ\text{C}$  (298K) taken from datasheet, B is Steinhart – Hart constant, also taken from datasheet for specified NTC sensor.

**4.13. Command «int»** sets the measurement interval for simultaneous mode in milliseconds.

**4.15. Command «def»** sets the calibration constants and deviation tangents to default values fabrication programmed.

**4.16. Command «p»** prints out current values of calibration constants and deviation tangents and magnetometer FW version.

## 5. Recording the magnetic data (extended design only)

Extended design of simple 3-axis fluxgate magnetometer system provides the possibility of recording magnetic field strength components measured into uSD card with GPS coordinates binding and afterwards to transfer data captured to PC for further analysis using e.g. Surfer Software.

A lot of records could be produced continuously while free place in uSD card still available. Each new one starting immediately when record switch was switched (STATUS LED blink), and continuing until it will not be press again

Each record is a text file has name «DDMMYY\_hhmmss.csv», where DD/MM/YY and hh:mm:ss are date and time of the moment record started. Record file has the following basic structure useful to be passed into Surfer Software:

|    | A        | B           | C           | D          | E       | F       | G       | H    |
|----|----------|-------------|-------------|------------|---------|---------|---------|------|
| 1  | UTC time | Latitude,N  | Longitude,E | Height,M   | Hx,nT   | Hy,nT   | Hz,nT   | t,°C |
| 2  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9568,4 | -8336,9 | 32229,4 | 15,6 |
| 3  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9553,6 | -8297,2 | 32229,4 | 15,6 |
| 4  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9560,4 | -8298,1 | 32253,7 | 15,6 |
| 5  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9566,8 | -8295,7 | 32253,7 | 15,5 |
| 6  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9576,3 | -8307,6 | 32240,0 | 15,6 |
| 7  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9567,4 | -8303,6 | 32240,0 | 15,6 |
| 8  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9567,3 | -8296,2 | 32302,6 | 15,6 |
| 9  | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9577,7 | -8296,2 | 32302,6 | 15,6 |
| 10 | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9579,6 | -8322,0 | 32275,0 | 15,6 |
| 11 | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9585,4 | -8334,3 | 32275,0 | 15,6 |
| 12 | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9585,3 | -8325,9 | 32275,0 | 15,6 |
| 13 | 19:12:36 | 5559.399414 | 5442.665527 | 213.699997 | -9579,2 | -8342,6 | 32250,5 | 15,6 |
| 14 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9577,6 | -8335,6 | 32250,5 | 15,6 |
| 15 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9579,4 | -8315,3 | 32260,2 | 15,6 |
| 16 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9578,3 | -8322,4 | 32260,2 | 15,6 |
| 17 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9569,1 | -8324,1 | 32266,4 | 15,6 |
| 18 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9577,4 | -8314,3 | 32266,4 | 15,6 |
| 19 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9572,6 | -8324,9 | 32250,0 | 15,6 |
| 20 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9576,6 | -8332,5 | 32250,0 | 15,6 |
| 21 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9573,1 | -8311,1 | 32261,4 | 15,6 |
| 22 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9575,7 | -8315,7 | 32261,4 | 15,7 |
| 23 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9576,3 | -8315,7 | 32236,1 | 15,6 |
| 24 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9576,0 | -8326,7 | 32236,1 | 15,6 |
| 25 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9576,3 | -8314,8 | 32215,0 | 15,6 |
| 26 | 19:12:37 | 5559.398438 | 5442.666016 | 214.600006 | -9569,1 | -8310,2 | 32215,0 | 15,6 |

Fig.5-1. Structure of magnetic field data record file

**POWER LED** tell us is magnetometer ready for measurements.

**STATUS LED** indicating if fault of the power state occurred and record state. It has 3 states: quiescent, flashing, and active.

Quiescent indicates that power supply is good.

Flash indicates the command was received now from USART or/and record to uSD card is active.

Active indicates supply voltage out of range, may be occurred if supply accumulator was discharged, or supply voltage higher than 16V was applied to system. When supply voltage is in the right range, the system starts working normally again and a new record is automatically created to save new magnetic data, if the record switch is not switched OFF. During this the LED will switch to quiescent state.

If fault of the power state occurs during active recording of the magnetic data, the recording stops and the current record file closes until supply voltage returns into the right range.

**GNSS LED** indicating if the data from GPS receiver are valid. It has 4 states:

- long triple flashing every 4 seconds indicating that GPS data are not valid yet because of not enough satellites detected yet;

- short single flashing blue LED every 1 second indicating that GPS data are valid and ready to be recorded together with magnetic data;

- active LED (continuously on while record switch is active) indicates the data recording fault. Data recording should be switched OFF and uSD card need to be checked;

Quiescent state of both LEDs together indicates the system is not working, since no power supply applied or uSD card was not initialized at the system launch.

### **To record the magnetic data follow the sequence of steps below**

5.1. Power ON the magnetometer system, check if POWER LED in ON, wait until GNSS will produce short single flashes every 1 second;

5.2. Press record switch to start recording;

5.3. Press record switch again to stop recording;

5.4. Connect magnetometer system to PC using micro USB cable (not included!), wait until PC operating system automatically install required USB flash disk driver;

5.5. Open installed flash disk using file explorer, copy the records to PC;

5.6. Disconnect the magnetometer system from PC.

## 6. Solving sensor axes deviation problem

Main advantage of 3-axis fluxgate magnetometer system is simultaneous measuring both magnetic field strength vector components  $H_x$ ,  $H_y$ ,  $H_z$ , and absolute value of magnetic field vector:  $H = \sqrt{H_x^2 + H_y^2 + H_z^2}$ .

To measure magnetic field strength vector components  $H_x$ ,  $H_y$ ,  $H_z$  directly we have to place fluxgate sensors ideally orthogonally to each other. In the practice magnetic field sensor axis has some deviation from ideal orientation, so we need to get exact expressions to calculate true magnetic field strength vector components  $H_x$ ,  $H_y$ ,  $H_z$  from measured values.

Now let's calculate the true  $H_z$  value from  $H_z^*$  actually measured for the z-axis only, then distribute the result obtained to other axes. Let's presume the angles between  $H_z^*$  vector projections to xz and yz planes are known, let's call them  $\alpha_{xz}$  and  $\alpha_{yz}$  respectively (fig.6-1).

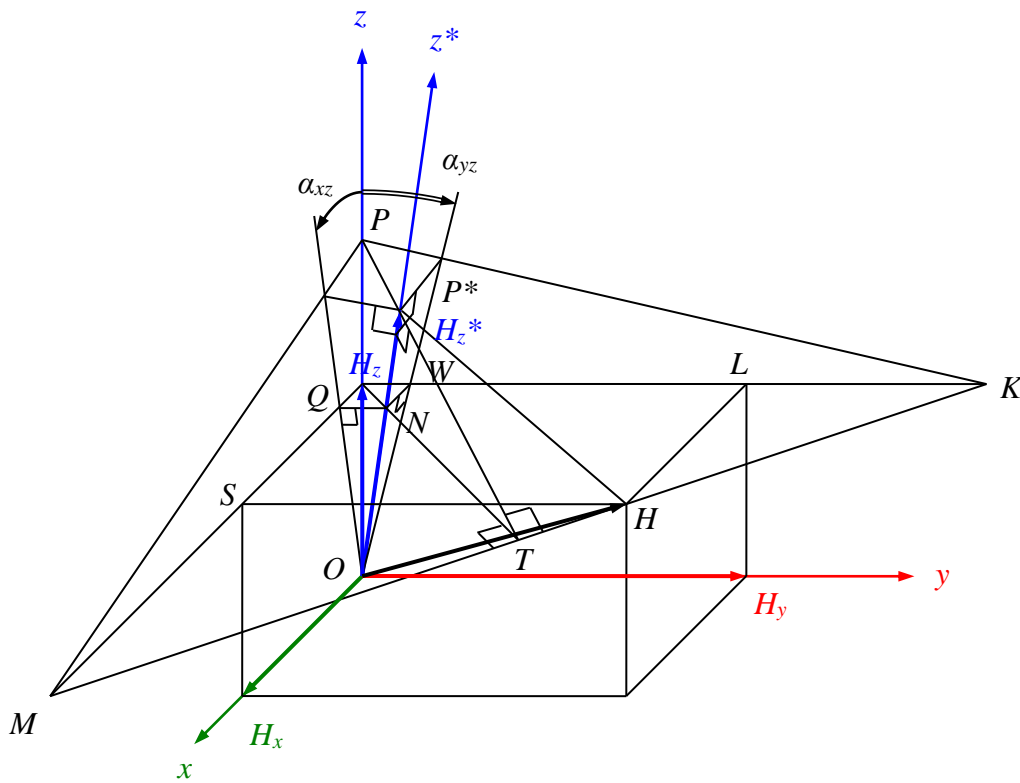


Fig.6-1. When axis of fluxgate sensor  $z^*$  deviates from true  $z$ -axis

So, we have to find relation between  $H_z$  and  $H_z^*$  depending on  $\gamma$  and  $\beta$  parameters.

$$H_z^* = OP^* = ON + NP^* \tag{6.1}$$

$$ON = \sqrt{OH_z^2 + NH_z^2} = \sqrt{OH_z^2 + QH_z^2 + WH_z^2} = H_z \sqrt{1 + tg^2 \alpha_{xz} + tg^2 \alpha_{yz}} \tag{6.2}$$

Let's,  $ON$  is calculated now. The calculation of  $NP^*$  will require a bit more effort:

$$\frac{NP^*}{NT} = \frac{NH_z}{ON} \Rightarrow NP^* = \frac{NT \times NH_z}{ON} \quad (6.3)$$

$$\begin{aligned} H_z Q &= H_z \operatorname{tg} \alpha_{xz} & H_z W &= H_z \operatorname{tg} \alpha_{yz} \\ H_z S &= H_x & H_z L &= H_y \\ SM &= H_z \frac{\operatorname{tg} \alpha_{yz}}{\operatorname{tg} \alpha_{xz}} & LK &= H_z \frac{\operatorname{tg} \alpha_{xz}}{\operatorname{tg} \alpha_{yz}} \end{aligned} \quad (6.4)$$

$$NH_z = \sqrt{QH_z^2 + WH_z^2} = H_z \sqrt{\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}} \quad (6.5)$$

Let's,  $ON$  and  $NH_z$  are calculated now. Only  $NT$  calculation required in order to determine  $NP^*$  from expression 6.3 in terms of  $\alpha_{xz}$ ,  $\alpha_{yz}$ , and  $H_z$ .

$$NT = TH_z - NH_z = MH_z \cos(MH_z T) - NH_z = MH_z \cos(NH_z Q) - NH_z \quad (6.6)$$

$$\begin{aligned} MH_z &= H_x + H_y \frac{\operatorname{tg} \alpha_{yz}}{\operatorname{tg} \alpha_{xz}} \\ NH_z &= H_z \sqrt{\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}} \\ \cos(MH_z T) &= \frac{QH_z}{NH_z} = \frac{\operatorname{tg} \alpha_{xz}}{\sqrt{\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} \end{aligned} \quad (6.7)$$

Insert expressions (6.7) into (6.6) to obtain  $NT$ :

$$NT = \frac{H_x \operatorname{tg} \alpha_{xz} + H_y \operatorname{tg} \alpha_{yz}}{\sqrt{\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} - H_z \sqrt{\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}} \quad (6.8)$$

Insert expressions (6.2), (6.5), and (6.8) into (6.3) to obtain  $NP^*$ :

$$NP^* = \frac{H_x \operatorname{tg} \alpha_{xz} + H_y \operatorname{tg} \alpha_{yz} - H_z (\operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz})}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} \quad (6.9)$$

Insert expressions (6.2) and (6.9) into (6.1) to obtain desired  $H_z^*$ :

$$H_z^* = H_x \frac{\operatorname{tg} \alpha_{xz}}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} + H_y \frac{\operatorname{tg} \alpha_{yz}}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} + H_z \frac{1}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz} + \operatorname{tg}^2 \alpha_{yz}}} \quad (6.10)$$

Check some special cases:

If  $\alpha_{xz} = \alpha_{yz} = 0$  then  $H_z^* = H_z$ ;

If  $\alpha_{xz} = 0$  then  $H_z^* = H_y \frac{\operatorname{tg} \alpha_{yz}}{\sqrt{1 + \operatorname{tg}^2 \alpha_{yz}}} + H_z \frac{1}{\sqrt{1 + \operatorname{tg}^2 \alpha_{yz}}}$ ;

If  $\alpha_{yz} = 0$  then  $H_z^* = H_x \frac{\operatorname{tg} \alpha_{xz}}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz}}} + H_z \frac{1}{\sqrt{1 + \operatorname{tg}^2 \alpha_{xz}}}$ .

Now look at the most general case when all 3 sensor axes deviate from the true  $x$ -,  $y$ -, and  $z$ -axis. Let's presume angles between  $H_x^*$  vector projections to  $xz$  and  $xy$  planes are  $\alpha_{zx}$  and  $\alpha_{yx}$  respectively, angles between  $H_y^*$  vector projections to  $yz$  and  $xy$  planes are  $\alpha_{zy}$  and  $\alpha_{xy}$

Since axis of one of fluxgate sensor can be used as true, let sensor  $z^*$  to coincide with true  $z$ -axis, so  $\alpha_{xz} = \alpha_{yz} = 0$ ,  $H_z^* = H_z$ . From expression (6.10) we obtain  $H^*_{xyz} \rightarrow H_{xyz}$  transform:

$$\begin{aligned} H_x^* &= H_x f(\alpha_{yx}, \alpha_{zx}) + H_y g(\alpha_{yx}, \alpha_{zx}) + H_z f(\alpha_{zx}, \alpha_{yx}) \\ H_y^* &= H_x f(\alpha_{xy}, \alpha_{zy}) + H_y g(\alpha_{zy}, \alpha_{xy}) + H_z f(\alpha_{zy}, \alpha_{xy}) \\ H_z^* &= H_z \\ \text{where} & \end{aligned} \tag{6.11}$$

$$f(\alpha_1, \alpha_2) = \frac{tg\alpha_1}{\sqrt{tg^2\alpha_1 + tg^2\alpha_2 + 1}}$$

$$g(\alpha_1, \alpha_2) = \frac{1}{\sqrt{tg^2\alpha_1 + tg^2\alpha_2 + 1}}$$

And, skipping intermediate calculations, inverse transform  $H_{xyz} \rightarrow H^*_{xyz}$  expressions:

$$\begin{aligned} H_x &= \frac{-H_x^* \sqrt{1 + tg^2\alpha_{yx} + tg^2\alpha_{zx}} + H_y^* \sqrt{1 + tg^2\alpha_{xy} + tg^2\alpha_{zy}} + H_z^* (tg\alpha_{zx} - tg\alpha_{zy}tg\alpha_{yx})}{1 - tg\alpha_{xy}tg\alpha_{yx}} \\ H_y &= \frac{H_x^* \sqrt{1 + tg^2\alpha_{yx} + tg^2\alpha_{zx}} - H_y^* \sqrt{1 + tg^2\alpha_{xy} + tg^2\alpha_{zy}} + H_z^* (tg\alpha_{zy} - tg\alpha_{zx}tg\alpha_{xy})}{1 - tg\alpha_{xy}tg\alpha_{yx}} \\ H_z &= H_z^* \end{aligned} \tag{6.12}$$

Deviation tangents  $tg \alpha_{zx}$ ,  $tg \alpha_{yx}$ ,  $tg \alpha_{zy}$ ,  $tg \alpha_{xy}$ , can be measured directly or fitted using differential evolution technique.