Synchronization of Independent Sensors' Measurements (Scan Fish)

Vol.1 – The "saw-effect" causes on the magnetic field vertical gradient plots, adjusting the measurements' transmission channel, evaluating the "constant delay" influence because of the power supply time to the magnetometer

Rev. 1.1

R.V. Geo Ranger
08.04.2024

SEA

Content

History of changes

Version	Date	Description of changes
1.0	2023-12-03	The document was created by Ivan D.
1.1	2024-04-08	The text has been edited by Ivan D.

List of Figures

Tables list

From the author

The content of the document introduces three particular features in how the Scan Fish works:

-- magnetic sensor measurements are time-based by the logging program at the data acquisition time, not by the hardware at the measurement time;

-- the digital channel of data transmission from the magnetic sensor to the recording program might have delays;

-- magnetic sensors are not synchronized with each other and perform measurements as completely separate pieces of the equipment.

These specific features need both additional mathematical processing to bring the magnetometer measurements to uniform time marks and the need for additional equipment tuning.

Were this document to be written now, its structure and way of presentation would be quite different. It would probably be structured along the lines of "statement of assertion, presentation of justification". However, the first pages of the paper have been written when the *saw-tooth effect* (relatively high-amplitude "teeth" in magnetic field gradient plots) had just been discovered, and the magnetometer registration system in QINSy, built on the use of a *magnetometer-trigger*, was "de facto standard" and uncontroversial. Initially, the first pages of the document contained a description of the saw-tooth effect found. Then the document was supplemented with the test measurements and experiments performed. Accordingly, the whole narrative is organized based on the following principle: first, description of an incomprehensible effect, then search for the underlying reason, the supposed cause of the effect, and finally the results of its removal.

We can identify the following steps in writing the document:

-- Detecting the saw-effect on magnetic field recordings (Introduction, Chapter 1 and Chapter 2);

-- Detecting severe delays in the data channel from Scan Fish to QINSy. We performed a series of experiments (Appendix 1) and reduced the delay level to an acceptable one (Chapter 3);

-- Detecting the magnetometers measurements at Scan Fish to be not synchronized (Chapter 4);

-- The *algorithmic synchronization* method was applied and the results obtained (Chapter 5). The algorithm and mathematical techniques applied in algorithmic synchronization are outlined in Part 2, which is arranged as a separate document;

-- Comparative analysis of the data processed with and without algorithmic synchronization (Chapter 6) was also used along with analyzing the "measurement time delays" effect on the shape and position of magnetic anomalies (Chapter 7).

For the reader, whose plans do not include mentally going through all the stages of the experiments and consistently finding the causes and the effects that are identified by the data, the best solution will be to start reading the document with the Conclusion, and then to read the main text, taking it as a justification of the conclusions which they already know.

Introduction. Problem statement

Initial conditions. A magnetic survey is performed using Scan Fish, with two rows of 4 G-882 magnetometers installed (each magnetometer is connected individually). Magnetic field (T) measurements are recorded in the 8Mag-log file containing measurements of eight magnetometers.

Problem description. ***The saw-tooth effect*** (hereafter referred to as *"the saw-effect"* or just *"the saw"*) is formed on the plots of the vertical gradient (VG) of the magnetic field (the difference between the measurements of magnetometers 1-2, 3-4, 5-6, 7-8). We need to determine the cause of the saw and remove it from the vertical gradient graphs. An example of four vertical gradient plots with the saw-effect is shown in ***Figure 0.1***.

An additional feature is that sensors 1-2 show no saw effect (***Figure 0.1***, blue arrow).

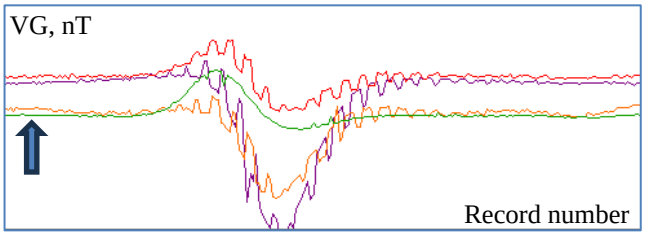


Figure 0.1 Plots of a vertical gradient with the saw-effect, VG plots

The magnetic field plots' analysis shows "periodically repeated measurements" (***Figure 0.2***). We can take the following as an initial assumption: for some reason the data of one magnetometer "***freeze***" (hereafter this word will be used to refer to the repetition of a magnetometer measurement), while the one paired to it performs the next measuring. Due to this "freezing", a saw is formed in areas with a high magnetic field gradient. Therefore, one should analyze the time delays in the data flow from the magnetic sensor to QINSy to fully understand the process.

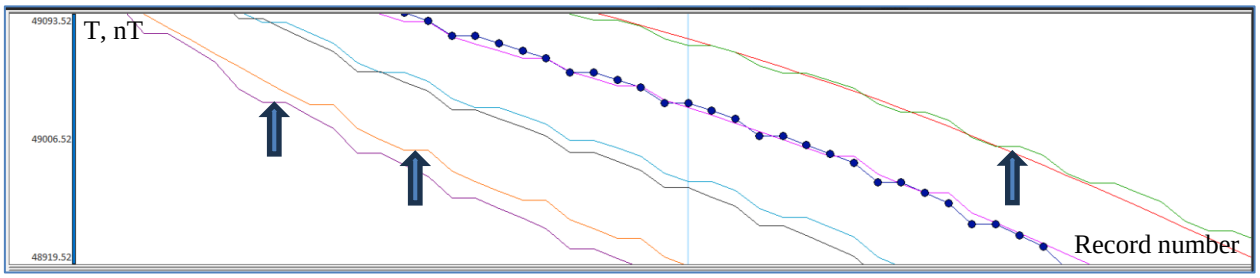


Figure 0.2 Periodically repeated measurements on magnetic field plots, T plots

An example of the saw-effect for Scan Fish with 10 magnetometers is shown in ***Figure 0.3***. Some "teeth" distorting the signal have an amplitude of more than 100nT.

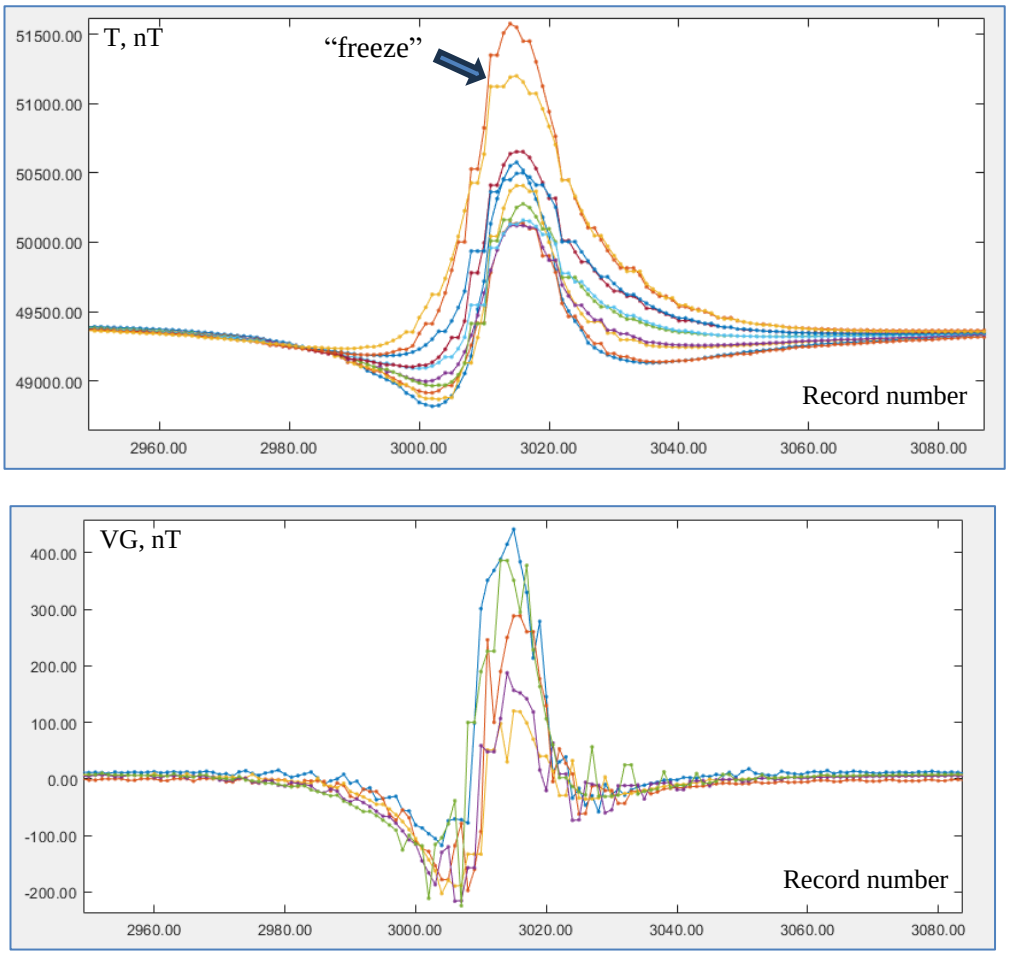


Figure 0.3 The saw-effect example: Scan Fish, 10 magnetometers, T and VG plots

Forceful solution of the problem. The saw could be partially removed by applying B-spline or other smoothing methods to the original magnetic field, whereas the "frozen" measurements are shifted as a result of averaging, thus the saw is strongly weakened. *Figure 0.4* shows an example of using B-spline.

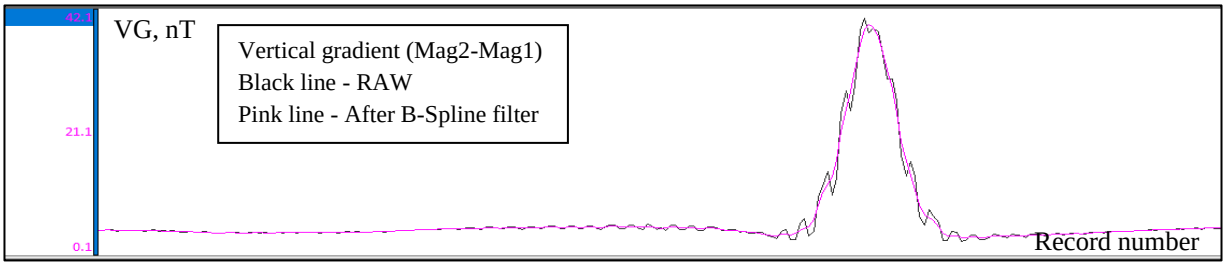


Figure 0.4 B-spline averaging result, VG plot

However, the shape of magnetic anomalies is not accurately restored with this approach. First, the magnetic field is averaged to the middle of the "saw teeth", which does not correspond to reality (the real curve runs along the top or the bottom of the "saw"); Second, the averaging results contain short-period bends (not completely smoothed "saw teeth"), thus distorting the shape of the real magnetic anomaly. For more details, see Chapter 6 which describes application of smoothing processing.

1. Describing the data transmission channel from magnetometers to QINSy

Figure 1.1 shows a chart of the data flow from the magnetometers to QINSy.

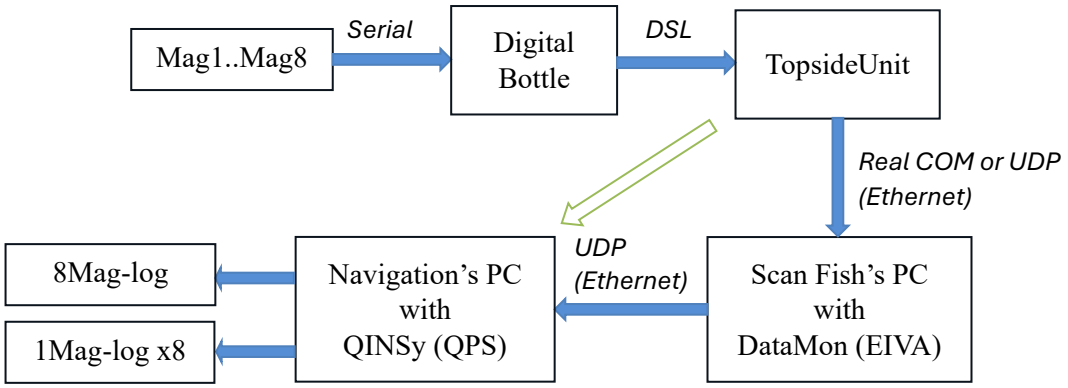


Figure 1.1 A chart of data flow from magnetometers to QINSy

Data are transmitted via a parallel interface (like RS-428) from the G-882 magnetometers to the digital module installed on Scan Fish. After that, the data (probably using an interface like a DSL-modem) are transmitted via a coaxial cable to the TopsideUnit installed in a laboratory. Next, the data are transmitted via Ethernet to a computer with DataMon software installed (the default protocol used for transmission is Real COM, but UDP can also be used). The DataMon reformats the data and transmits them via Ethernet over UDP to the navigation computer with QINSy software installed, which writes them into the 8Mag-log file.

An alternative way of data transmission (shown in ***Figure 1.1*** by the green arrow) is sending data from TopsideUnit directly to QINSy, eliminating the data reformatting in DataMon.

QINSy

The magnetometer serving as the "trigger" is selected in QINSy (usually Mag1 is selected). When a measurement from this magnetometer is received, the current data (the most recent measurements from all eight magnetometers up to that point) are written into the ***8Mag-log file***.

The absence of the “saw” on the vertical gradient for sensors 1-2 (***Figure 0.1***, blue arrow) could be assumed to depend on the fact that Mag1 was selected as the trigger.

Besides the 8Mag-log, separate logs for each magnetometer (***1Mag-log*** x8) were established in QINSy to analyze delays of data arrival. These logs are recorded when a measurement is received from each magnetometer.

Port-servers

The physical connectors on the Digital Bottle, which serve to transmit data to the TopsideUnit, are matched with 2 ***port-servers*** of 4 ports each (8 ports on the whole). Scan Fish hosts 3 Digital Bottles, i.e., there are 24 ports for data transmission. Both magnetometers and other sensors (MRU, SVP, Altimeter,

Depth sensor) are transmitting data through the port-servers. ***Table 1.1*** shows the configuration of connecting magnetometers to the port-servers for both Scan Fish.

Table 1.1 Configuration of magnetometers' connection to the port-servers

<table>
<tr><th colspan="2">Port Scan Fish</th><th colspan="2">Starboard Scan Fish</th></tr>
<tr><td>Mag1</td><td rowspan="4">PServ_1PS</td><td>Mag1</td><td rowspan="4">PServ_1SB</td></tr>
<tr><td>Mag2</td><td>Mag2</td></tr>
<tr><td>Mag3</td><td>Mag3</td></tr>
<tr><td>Mag4</td><td>Mag4</td></tr>
<tr><td>Mag5</td><td rowspan="3">PServ_2PS</td><td>Mag5</td><td>PServ_2SB</td></tr>
<tr><td>Mag6</td><td>Mag6</td><td rowspan="3">PServ_3SB</td></tr>
<tr><td>Mag7</td><td>Mag7</td></tr>
<tr><td>Nag8</td><td>Nag8</td></tr>
<tr><td colspan="4">PServ_1PS – ver. 82000747_2, 10/19/2020; IP10.10.103.101
PServ_2PS – ver. 82000747_2, 10/19/2020; IP10.10.103.104
PServ_1SB – ver. 82000747_AA, 06/17/2022; IP10.10.103.101
PServ_2SB – ver. 82000747_2, 10/19/2020; IP10.10.103.105
PServ_3SB – ver. 82000747_AA, 06/17/2022; IP10.10.103.104</td></tr>
</table>

2. A method of estimating delays in a data transmission channel

Magnetometers are equipped with a precise quartz crystal clock, since the magnetic field is calculated through "precession counting", with a quartz clock involved (not an exact expression for a quantum magnetometer, but in general their principle is similar to a proton one). Therefore, the periodicity of measurements in magnetometers is very stable. On these grounds, the time error of measurements' transmission over the digital channel can be estimated by subtracting the time of the previous measurement (for one magnetometer) from that of the current measurement, thus obtaining the calculated *time step between measurements* or the ***time step*** (it can also be called the period of measurements).

The plot obtained from the resulting calculations for the time registered in 8Mag-log file is shown in ***Figure 2.1***. The horizontal axis shows the measurement number, while the vertical one shows the step or period of measurement. Since Mag1 was used as the trigger, the time step is actually estimated for Mag1.

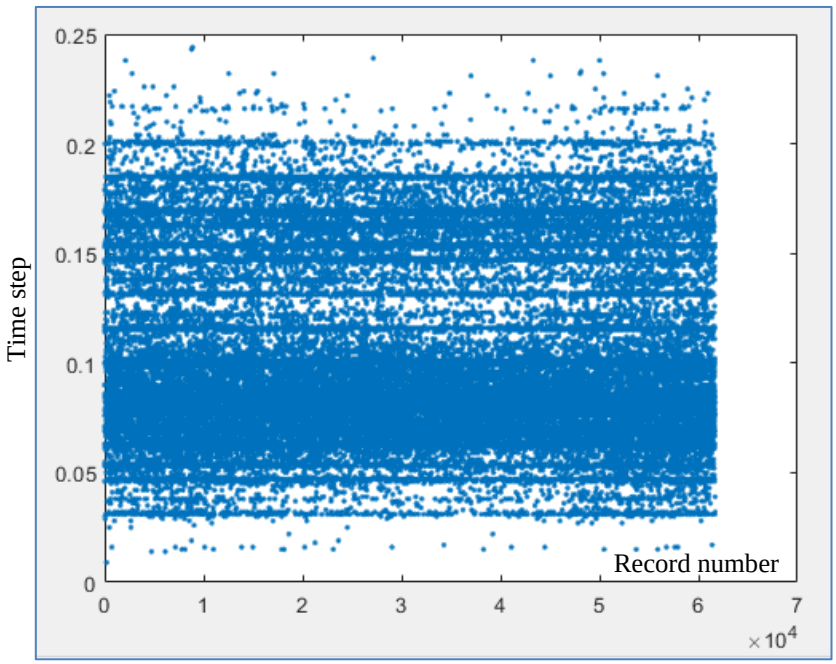


Figure 2.1 Measurement step (measurement period) in time

The measurement hardware step (period) for all eight magnetometers was set to 0.1 seconds. One can see the plot showing a significant spread in the time step from 0.01 seconds to 0.24 seconds. Time jumps of magnetometer measurements over time with respect to the magnetometer-trigger by an amount greater than the hardware measurement period will result in no "time jump" magnetometer data arriving in QINSy between triggers. This, in turn, will force QINSy to keep repeating the previous measurement values instead of the missed one (i.e., we'll see the "data freezing" shown in ***Figure 0.2***). This "freezing" will result in a "saw" in the calculation of the vertical gradient (with "teeth" or "freeze intervals" up to 4 measurements wide). The "saw" will be especially strong in the areas with a high magnetic field gradient.

Figure 2.2 shows the data transmission delays for eight magnetometers (8 rows of points of different colors) plotted against 1Mag-log files for each magnetometer. The horizontal axis shows the measurement number while the vertical axis shows the measurement time (unlike the "measurement step"

which is shown on the vertical axis in ***Figure 2.1***). Arrows show the places of delays and omissions of measurements.

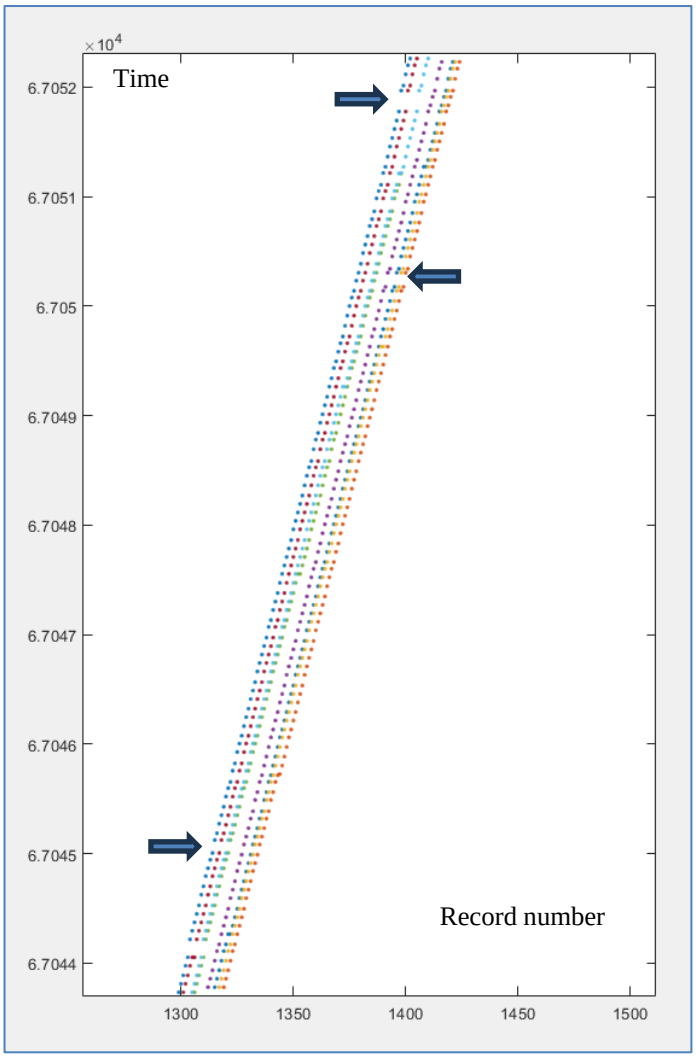


Figure 2.2 Data arrival delays for 8 magnetometers shown on the time axis

The magnetometer-trigger measurements will be transmitted to QINSy with delays (with time-steps from 0.01 to 0.24 seconds). QINSy will determine (and write into the 8Mag-log file) the magnetometer coordinates according to a trigger also with delays. ***Figure 2.3*** provides an example of a 0.009 second time step between recordings. The same is true for other sensors that QINSy writes into the 8Mag-log file.

```
206 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:17.818,EC10-14_077,4      ,5      0,4.20,-2.63,160.8
207 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:17.887,EC10-14_077,4      ,5      1,4.20,-2.63,160.8
208 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:17.971,EC10-14_077,4      ,5      ,4.20,-2.63,160.8
209 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.141,EC10-14_077,4      ,5      ,4.20,-2.63,160.8
210 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.280,EC10-14_077,4      ,5      ,2.93,-2.01,160.8
211 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.289,EC10-14_077,4      ,5      ,2.93,-2.01,160.8
212 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.388,EC10-14_077,4      ,5      ,2.93,-2.01,160.7
213 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.573,EC10-14_077,4      ,5      ,2.93,-2.01,160.7
214 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.657,EC10-14_077,4      ,5      2.93,-2.01,160.7
215 0052_GRA_NOR_ECR_EC10-14_077_MBES--0001.db,08/12/2023,10:01:18.720,EC10-14_077,4      ,5      2.93,-2.01,160.8
```

Figure 2.3 A step between recordings of 0.009 seconds with a hardware measurement period of 0.1 seconds

Consequently, along the magnetometer trajectory in terms of distance along the track, the points will also be distributed unevenly: either close to one point or at a double distance. With a vessel speed of 4 knots and a recording frequency of 10 Hz, the distance between the measurements will vary from 0 to 40 cm with a real distance of 20 cm. However, the vertical gradient calculation will be mostly affected by the described data arrival delays (***Figure 0.1***).

3. Delay analysis for various data transmission channel settings

To analyze the dependence of delays on the equipment settings, a series of experimental recordings were performed under a port conditions (the vessel is moored, Scan Fish and magnetometers are on board). The following measurement system settings have been changed:

-- magnetometers' measurement logging frequency at 14, 12, 10 Hz;

-- data logging with UDP and RealCom protocols (for port-servers);

-- data logging during transmission via DataMon and with a TopsideUnit-QINSy direct connection (see green arrow in ***Figure 1.1***).

Measurement step (time-step) graphs plotted for various settings and equipment configurations are given in Appendix 1. Based on the results of the time-step graphs analysis, the following conclusions can be made:

1) The RealCom protocol cannot be used when the magnetometers' measurement frequency exceeds 10Hz. Probably, the data transfer channel bandwidth does not allow it. When setting the measurement frequency of the magnetometers at 14Hz, the measurement reception frequency is approximately 12Hz (Appendix 1, Figures: 1_COM_14Hz_PS-Mon, 2_COM_14Hz_SB). There are a lot of data skips appear for the measurement frequency of 12Hz in the data flow (Appendix 1, Figures: 11_COM_12Hz_PS, 12_COM_12Hz_SB-Mon).
2) The 14Hz magnetometers' measurement frequency can be recorded using the UDP protocol when not connected via DataMon (Appendix 1, Figures: 4_UDP_14Hz_SB, 5_UDP_14Hz_PS). However, more data skips will occur, with the PServ_2 port-server having skips of two consecutive samples (Appendix 1, Figure 5_UDP_14Hz_PS). With a DataMon connection, the number of skips will increase.
3) The smallest variation in data transmission time (in time-step) occurs to meet the following configuration: UDP protocol is used to transmit data; magnetometers' measurement frequency is 10Hz; DataMon is excluded from the data transmission chain (Appendix 1, Figures: 13_UDP_10Hz_PS-Switch, 14_UDP_10Hz_SB-Switch in Appendix 1). This layout was selected as the ***working configuration*** to perform the geophysical survey.
4) While transferring data, each port-server (***Table 1.1***) has the features of its own. The features' description of the port-servers for the working configuration is given below.

   PServ_1PS demonstrates a small spread of time-step, approximately 0.0025 sec;

   PServ_2PS shows a small spread of time-step and periodic measurements skip (***Figure 3.1*** points to double time between data arrival and fewer number of received samples); skip of measurements occurs for PServ_2PS at any configuration of the measurement system;

   PServ_1SB – spread of time-step of 0.0025 sec for Mag1&Mag2; spread of 0.02-0.04 sec for Mag3&Mag4;

   PServ_2SB indicates spread of time-step 0.02-0.04 sec for Mag5;

   PServ_3SB – spread of time-step approximately 0.0025 sec for Mag6, Mag7, Mag8.

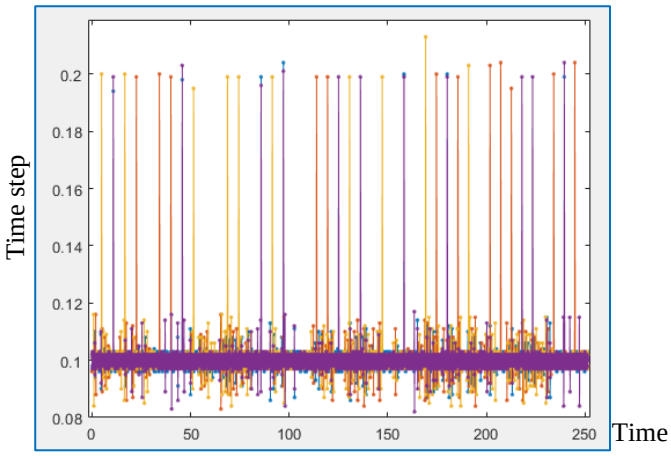


Figure 3.1 Measurements skipping by PServ_2PS port-server

A working configuration parallelizes the data flow through Network Switch and starts up with TopsideUnit separately in QINSy and separately in DataMon (*Figure 3.2*).

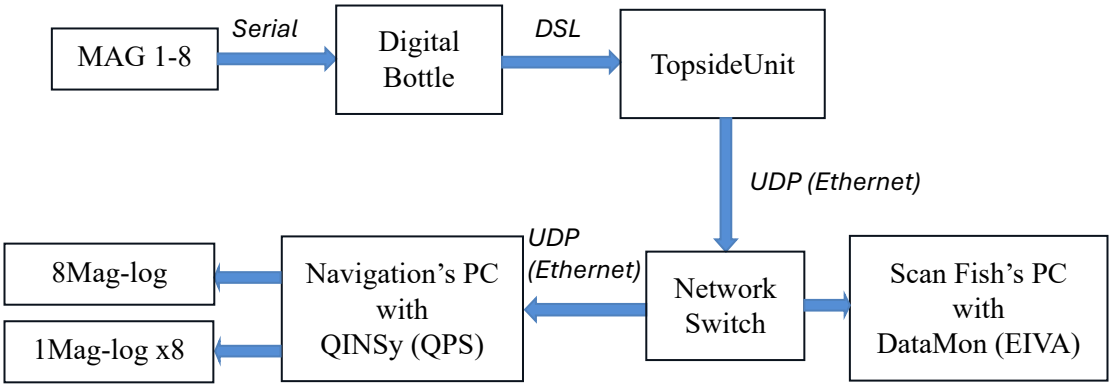
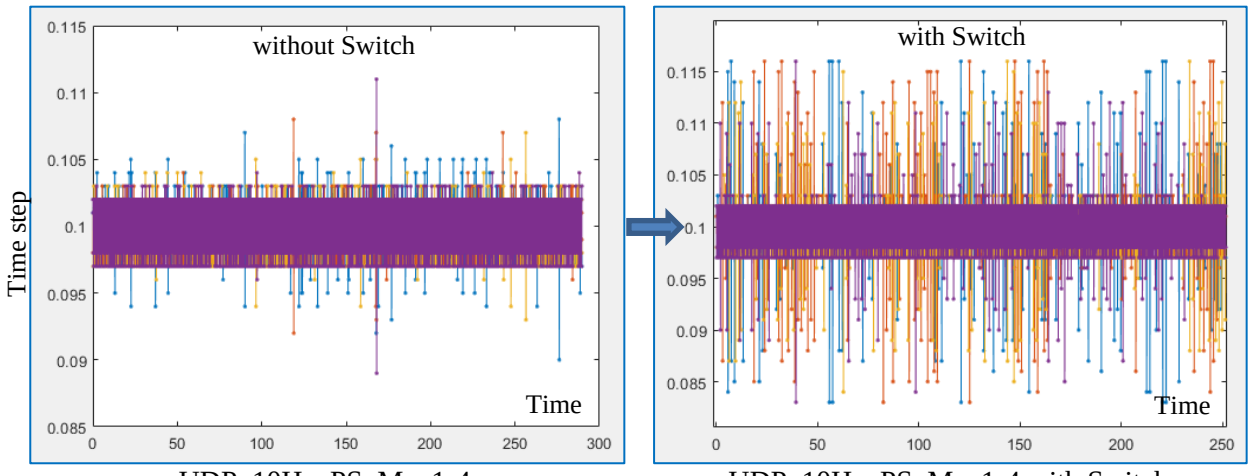


Figure 3.2 The working configuration chart of data transfer from magnetometers into QINSy

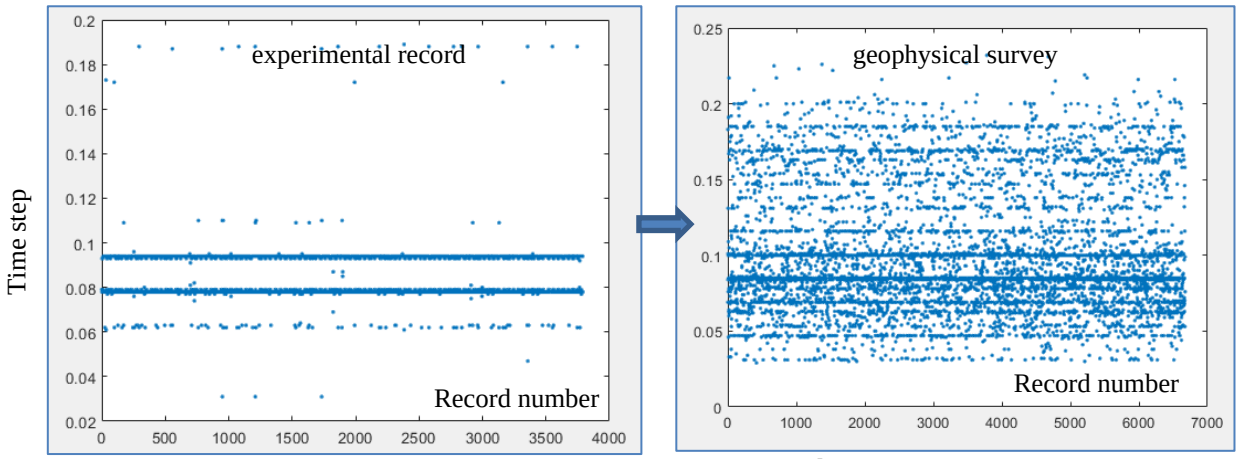
The Network Switch application resulted in sporadic delays which were absent with the direct TopsideUnit-QINSy connection (*Figure 3.3*).



UDP_10Hz_PS_Mag1-4 UDP_10Hz_PS_Mag1-4 with Switch

Figure 3.3 Appearance of delays when Switch is included in the data transmission channel

Another feature is that when performing experimental recordings under seaport conditions, the QINSy and DataMon software is not loaded with other calculations. Consequently, there will be less time-step spread in the experimental setup than when performing a geophysical survey. ***Figure 3.4*** demonstrates our point with an example we'll discuss in more detail below.



RealCom, DataMon, moored state
Mag3 Port SF

RealCom, DataMon, survey state
Mag3 Port SF

Figure 3.4 Increased time-step spread for geophysical survey

A comparison of the Port Scan Fish vertical gradients (calculated from two 8Mag-log files of different survey lines) for the initial configuration (RealCom, DataMon, 10Hz) and the working configuration (UDP, no DataMon, 10Hz) is shown in ***Figure 3.5***. The working configuration demonstrates a greatly reduced number of "saw teeth" (visually, more than 90% of the "saw teeth" have disappeared).

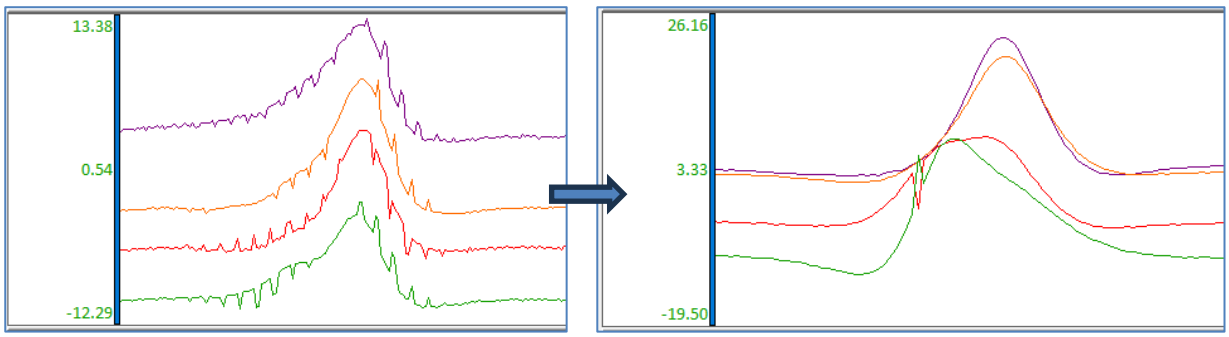


Figure 3.5 Comparing magnetic field vertical gradients for the initial and working configurations of the data transmission channel

4. The trigger-magnetometer performance analysis

After reducing the time-step spread to minimum values (working configuration), let us try to simulate the use of one magnetometer as a trigger based on the data in 1Mag-log files. To do this, we will add the missing values to the PServ_2PS measurements in the process (***Table 1.1***; ***Figure 3.1***). Eventually, the recordings of all the magnetometers for Port Scan Fish will have the same number of samples, and there will be no missing measurements in the recordings.

The upper part of ***Figure 4.1*** shows the time plotted on the horizontal axis; the charts of different colors present the measurements of Mag1, Mag2, Mag3, Mag4. We can identify two groups with four measurements of magnetometers, each group corresponding to one measurement cycle (we mean measurement cycles with a period of 0.1 sec). The red arrow points to the time delay between the measurement of the fourth and the first magnetometer. The ***Constant Delay*** components are shown by the blue arrows.

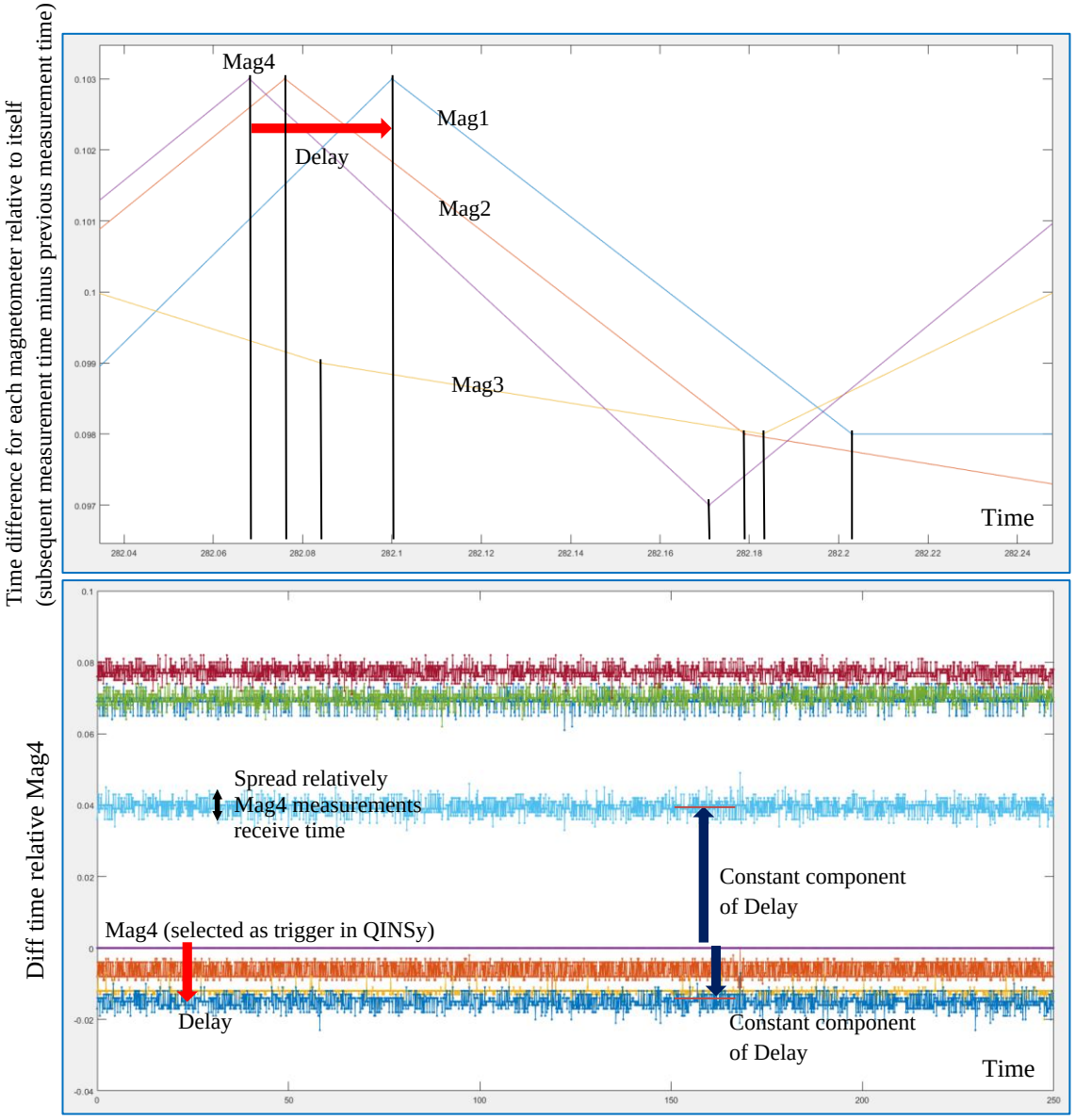


Figure 4.1 Plots of magnetometers' measurement delays versus Mag4 by UDP_10Hz_PS recording (skiped measurements are recovered for Mag5,6,7,8)

The horizontal axis in the bottom part of ***Figure 4.1*** also shows the time. The vertical axis shows the difference in the time of measurement arrival from the fourth magnetometer to all other magnetometers. That is, the fourth magnetometer is used as a trigger (its difference time of measurement will be equal to zero and will be represented by a horizontal line). The plots' measurements located in the negative range have not yet arrived to QINSy, however, the latter will register them at the next data arrival cycle initiated by the magnetometer-trigger (the plots will "kind of shift" into the 0.08-0.1 second range on the vertical scale).

Figure 4.1 also demonstrates a case, when Mag4 (purple color) or Mag8 (blue color) being used as a trigger, will have the recordings in the 8Mag-log file with no saw-effect.

Given Mag1 (blue) is chosen as the trigger, there is likely to be a saw-effect on the Mag3 (yellow) recording because the Mag1 chart sometimes crosses the yellow plot due to data spread. The consequence of such intersecting will be first the arrival of two measurements within the inter-trigger interval, and then no measurements between the triggers. This will cause the last QINSy measurement to be repeated and a "frozen" measurement to occur (an example of a "frozen" measurement is shown in ***Figure 0.2***).

Figure 4.1 has been plotted for a direct TopsideUnit-QINSy connection. Let's perform the same plotting to connect via Switch in the working configuration. ***Figure 4.2*** shows the results of such modelling.

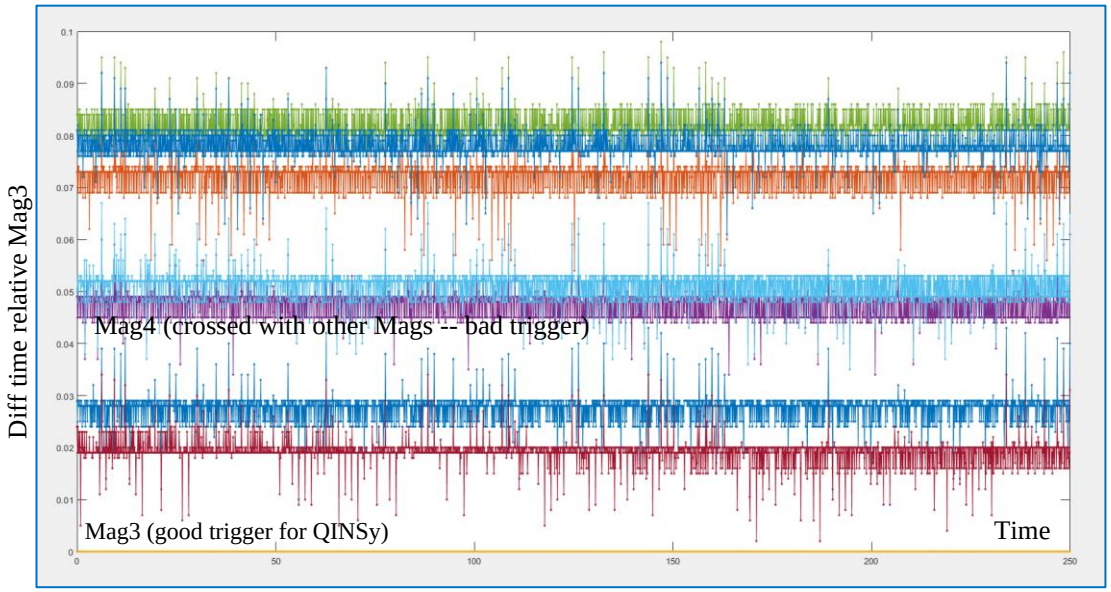


Figure 4.2 Measurement delays' plots of magnetometers against Mag3 by UDP_10Hz_PS-Switch recording (Mag5,6,7,8 recovered)

Two conclusions can be drawn from ***Figure 4.2*** analysis:

-- The additional noise generated by the Switch (compared in ***Figure 3.3***), caused all the plots to intersect except Mag3. Therefore, we chose it as the trigger; and thus, for the Mag3 trigger, the recordings in the 8Mag-log file will not contain the saw-effect. If any other magnetometer is selected as a trigger, the magnetic field plots will show "frozen" measurements, that will cause *single spikes* to occur on the magnetic field vertical gradient plots.

-- When comparing ***Figure 4.2*** and ***Figure 4.1***, we can conclude that with the system being restarted (the magnetometers are powered up), the relative position of the plots (and single measurements) on the time scale change. This means that after switching the system off and on, the Mag3 plot (see ***Figure 4.2***) will shift versus the other plots and may become unsuitable to function as a trigger.

Plots based on the data from the geophysical survey are shown in ***Figure 4.3*** (Port Scan Fish) and ***Figure 4.4*** (Starboard Scan Fish). All the missing values were pre-identified and filled in using linear interpolation results. The first channel (data transmission from Mag1) was taken as a trigger. As can be seen from the figures, the spread of the delays is stronger than for the experimental recordings done under the seaport conditions. This may be due to QINSy workload, resulting in the UDP message arrival time being determined with an error, or due to the Scan Fish-TopsideUnit channel being loaded with additional information related to the Scan Fish autopilot operation.

Figure 4.3 indicated that choosing the first channel as a trigger was successful for the data the channel contained. The 8Mag-log recording will have rare "frozen" measurements associated with the plots going beyond -0.1 sec line (***Figure 4.3***). Port Scan Fish will also reveal "frozen" measurements associated with the PServ_2PS port-server skipping data (***Figure 3.1***), though for the current figures these values have been determined and interpolated.

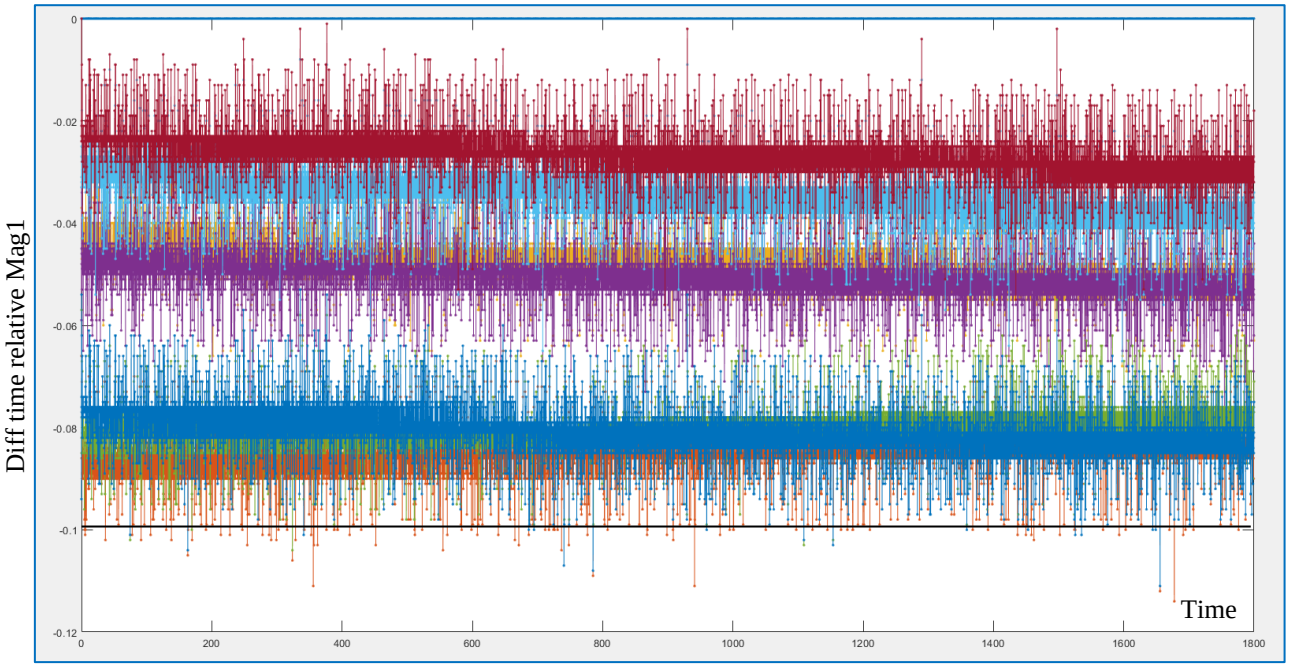


Figure 4.3 Plots of magnetometers measurements delays relative to Mag1 based on recording 0146_GRA_EC10-14_059_PS

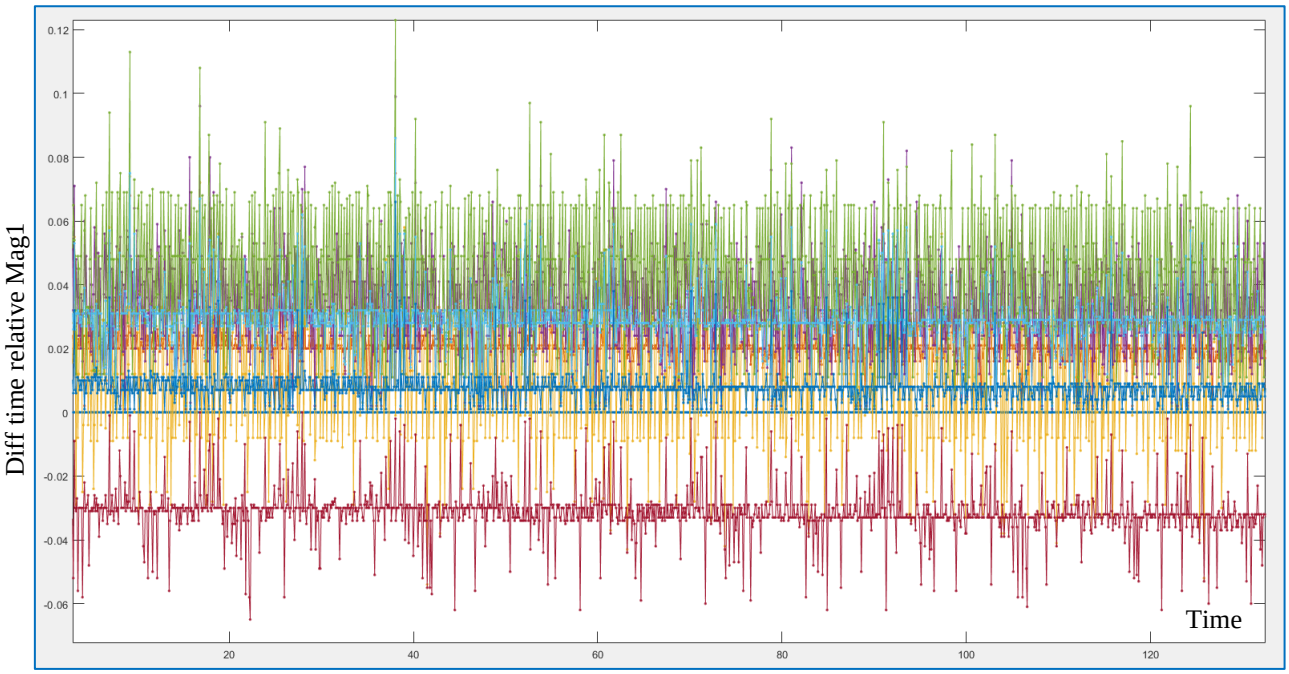


Figure 4.4 Plots of magnetometers measurements delays relative to Mag1 based on recording 0146_GRA_EC10-14_059_SB

To choose the first channel as a trigger for the data in ***Figure 4.4*** is not so good - the zero line is crossed many times by a yellow plot, which causes “freezing” and the “saw” emerging for Mag3 on the 8Mag-log recordings.

One can draw the following conclusions by analyzing the magnetometer-trigger performance:

1) Data skips (related to peculiarities of each port-server operation), when registering data with the magnetometer-trigger, will lead to “freezing” (duplication of the skipped values), which will cause single spikes to occur on the magnetic field vertical gradient plots;
2) With power on, the order of magnetometer measurements along the time axis is randomly set. When using a magnetometer-trigger, some of the magnetometer measurements can be recorded into the 8Mag-log file from the “previous measurement cycle”. For example, for ***Figure 4.1***, the measurements of magnetometers Mag1, Mag2, Mag3 will be obtained from the previous measurement cycle shifted in time by 0.09 seconds (actually 1 count);
3) Given a strong spread in the arrival time of measurements from the magnetometers (see example in ***Figure 2.1***), the recording into the 8Mag-log file will be complicated by a strong saw-effect;
4) The physical measurement periods of the magnetometers somewhat differ from 0.1 sec, which leads to a slow drift of the plots in ***Figure 4.3***. As a result, the zero line of the magnetometer-trigger will be gradually crossed by the plots for all other magnetometers, i.e., the “saw” will appear and disappear alternately on the vertical gradients calculated for different pairs of magnetometers.
5) One way to “increase the synchronization accuracy” for the 8Mag-log file could be to create a “virtual trigger” in QINSy (e.g., like a “virtual sounder”). In this case the measurements frequency will be exactly 0.1 sec; and there will be no spread in the arrival time of the magnetometer-trigger

measurements. Accordingly, the spread versus the trigger will not be the sum of two random values, which should reduce the variance by half and cut down the number of “jumps” over the trigger (the number of spikes due to the saw-effect).

5. Processing of data arrival time (algorithmic synchronization)

If the hardware settings do not allow to reduce the spread of measurement arrival time in QINSy up to the values allowing to write 8Mag-log reliably, one should use the methods of mathematical processing. For off-line processing, we used the data recorded separately for each magnetometer into the 1Mag-log file. Taken as a random normally distributed quantity, the measurement arrival time deviation in QINSy can be reduced by averaging in a sliding window. ***Figure 5.1*** shows an example of averaging the arrival time of measurements in a sliding window for 20 points and also of variance reduction (the raw data used are the same as for ***Figure 2.1***). The variance/spread value went down from 0.1 sec to about 0.05 sec. This processing made it possible to conditionally determine the exact arrival time of the magnetometer measurement and calculate the magnetic field vertical gradient without the saw-effect.

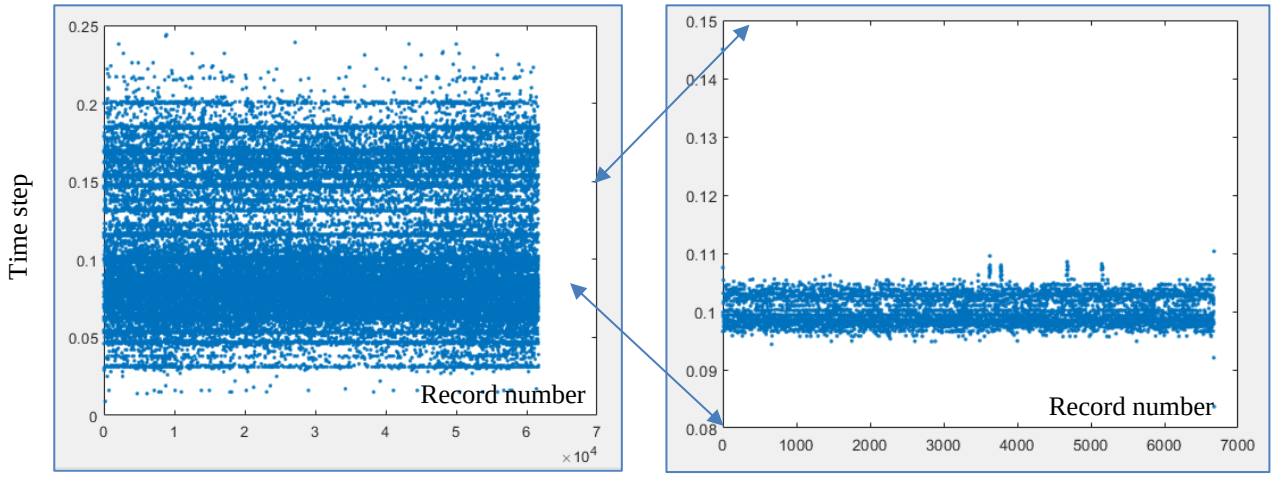


Figure 5.1 Spread reduction for time-step using averaging in a sliding window

Figure 5.2 compares magnetic field vertical gradient plots from 8Mag-log and 1Mag-log data recorded with their further processing.

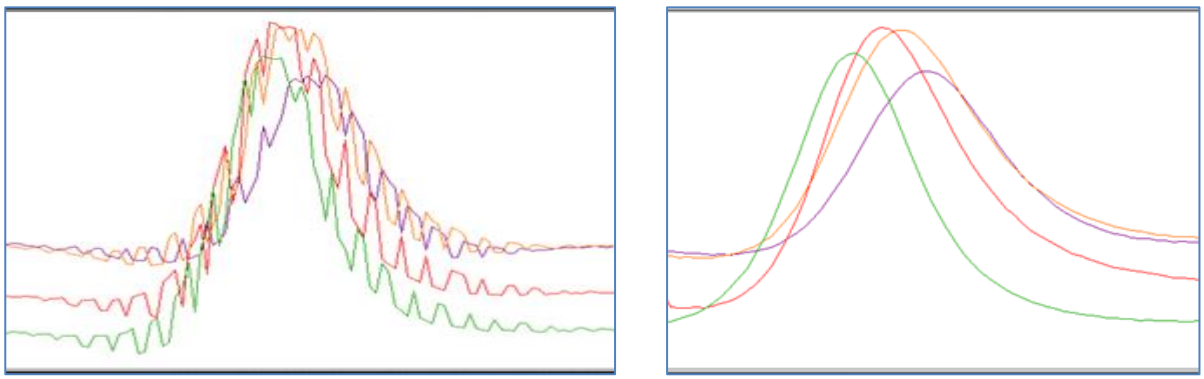


Figure 5.2 Comparing magnetic field vertical gradient plots from 8Mag-log and 1Mag-log data with further processing

Mathematical processing (in the simplest case - calculating the mean value for the measurement arrival time) can probably be done on-line. This will reduce the spread between time-steps (the arrival time of measurements) and make it possible to assemble a single string for magnetometers measurements on-

line and record into the 8Mag-log file with no saw-effect. The negative aspects of this approach are as follows:

-- complication of software settings;

-- on-line processing does not provide for individual specifics of port-servers (e.g., such as periodic data skipping, ***Figure 3.1***) and makes it impossible to identify these specifics from the recorded 8Mag-log;

-- the result of on-line processing becomes “irreversible”, i.e., if it fails, you cannot go back to the original data and re-process them.

For the reasons described above, the preferred method is to record individual magnetometers in 1Mag-log file with further processing of delays (hereinafter we will refer to such a processing as ***algorithmic synchronization).***

Another reason to use 1Mag-log recording and algorithmic synchronization is the “random Constant Delay” (***Figure 4.1***) between magnetometers measurements, which can be clearly seen in ***Figure 4.3*** and ***Figure 4.4***. The effect of this delay on the results of the data recording into the 8Mag-log file is described in more detail in Chapter 7.

6. Comparing results of smoothing and algorithmic synchronization

The result of removing the saw-effect using the algorithmic synchronization and comparing it with the smoothing performance is shown below.

Two examples of vertical gradient plots are presented which compare the results of smoothing and algorithmic synchronization. Smoothing was carried out in Oasis Montaj by using “rollingstats” (rollingstats.statistic=“6”; rollingstats.width=“5”; rollingstats.shrink=“1”). The upper part of ***Figure 6.1*** includes the raw data complicated by the saw-effect (8Mag-log file) and the result of smoothing using “rollingstats”. The lower part of ***Figure 6.1*** compares the plots on the smoothed data (8Mag-log file) and those based on data with synchronization of each magnetometer (1Mag-log files).

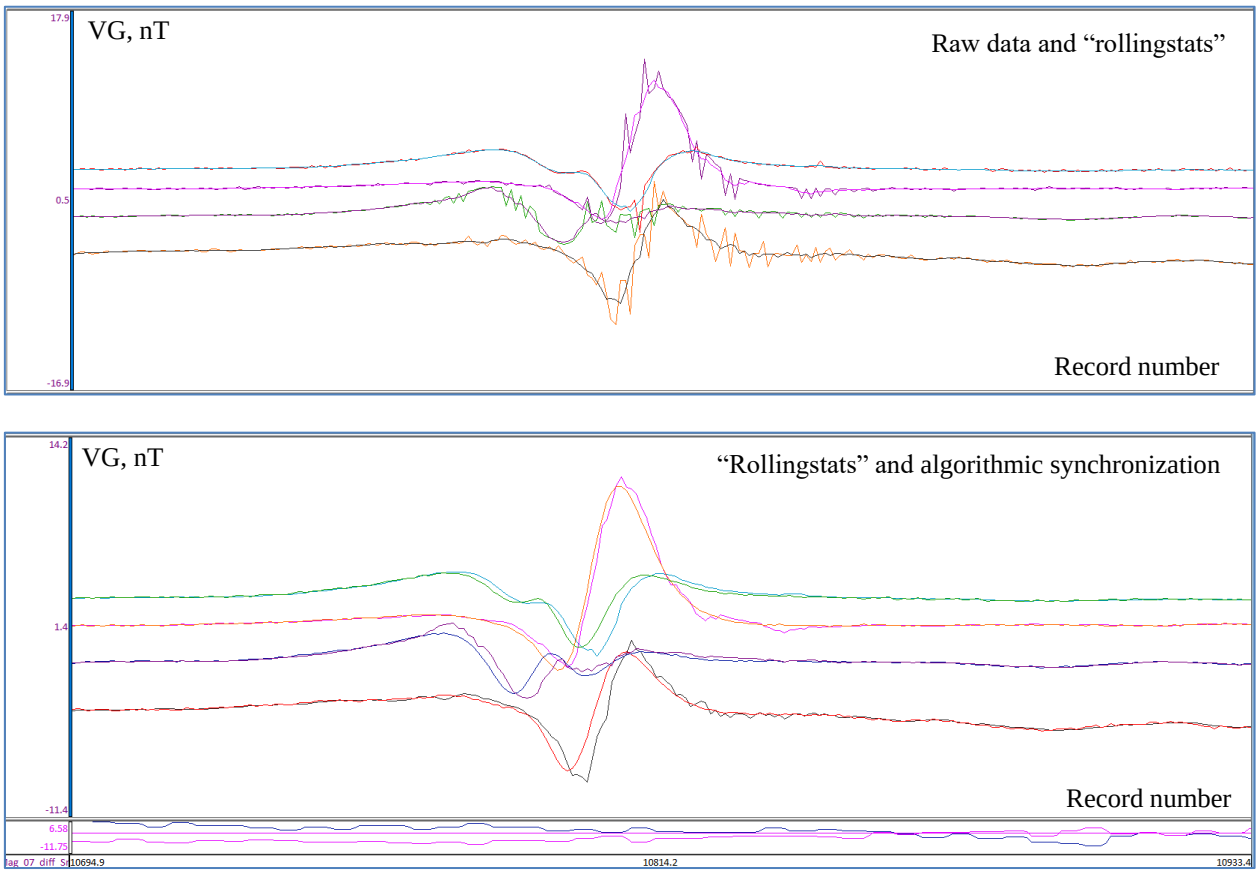


Figure 6.1 Comparing the result of using “rollingstats” with that of algorithmic synchronization, VG plots

As we can see by comparing the plots, the “smoothed” data in general are more “angular” than the “synchronized” ones. There is also a slight shift along the time axis (within the recording period – 0.1 seconds). However, no principal differences in the shape and position of the magnetic anomalies are found.

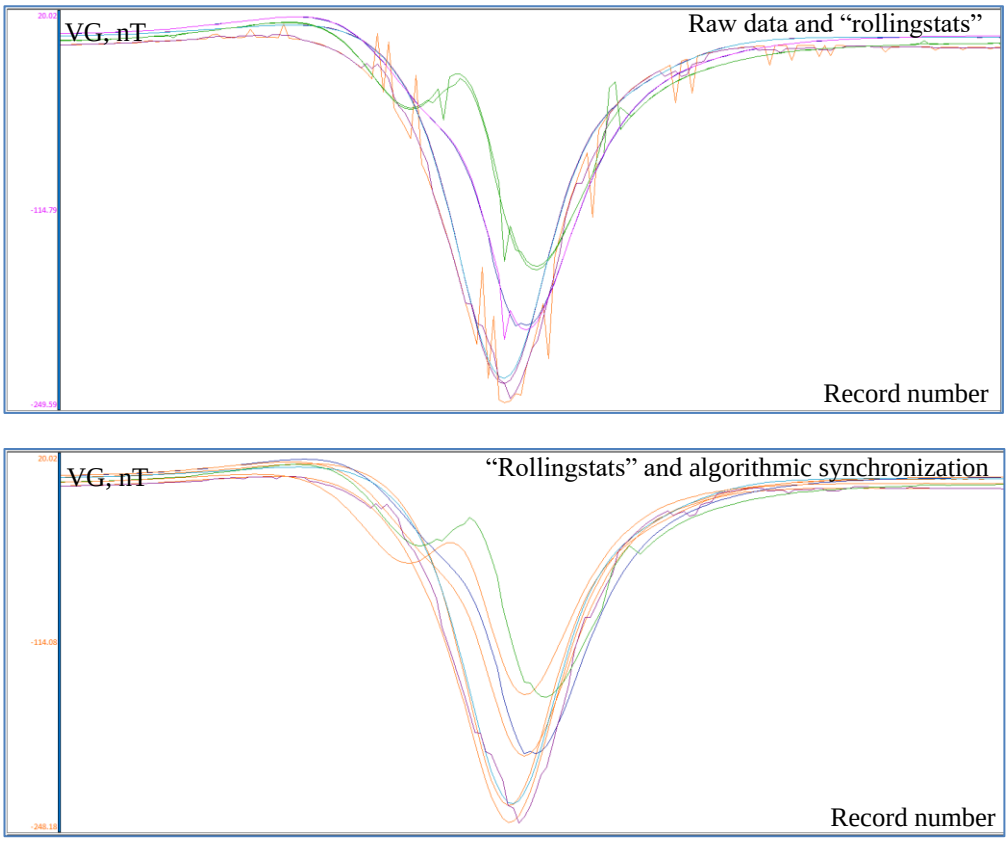


Figure 6.2 Comparing the result of using “rollingstats” with that of algorithmic synchronization (high amplitude anomaly), VG plots

Figure 6.2 shows the same comparison for a higher amplitude anomaly. The upper part represents the raw data complicated by the saw-effect (8Mag-log file) and also the result of smoothing using “rollingstats”. The lower part contains the result of smoothing (8Mag-log file) and synchronization (1Mag-log files). The plots show the same pattern as in ***Figure 6.1***, namely, the “smoothed” data are generally more “angular” than the “synchronized data”; there is a slight “shift” along the time axis caused by the accuracy of the time reference of the magnetometer measurements, from which the vertical gradient is calculated. However, there are no fundamental differences in the shape and position of the magnetic anomalies.

Thus, eliminating the cause of the “saw” by means of synchronization is preferable to “magnetic field smoothing”. However, the use of smoothing could be acceptable (to a first approximation) as there is no fundamental change in the shape or position of the vertical gradient anomaly. Except for the cases shown in ***Figure 7.1***.

7. “Constant Delay” effect on the VG calculation results

Figure 7.1 shows an unusual case of the saw-effect (purple line) when recording into the 8Mag-log file. Visually it resembles a modulated high-frequency oscillation. This effect occurs when the magnetometers (which serve to calculate the vertical gradient) pass over a magnetic anomaly that is characterized by a very weak vertical gradient (red and yellow plots) but a significant horizontal gradient (green plot).

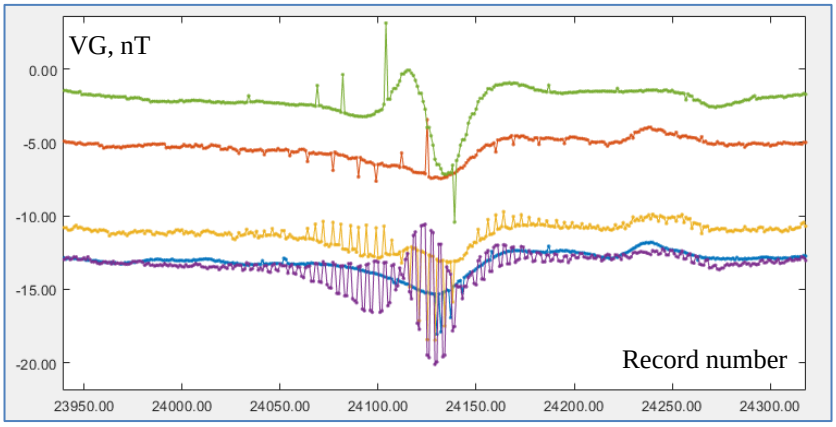


Figure 7.1 The saw-effect example: Scan Fish, 10 magnetometers, the VG plots, 8Mag-log file (50 counts on the horizontal scale correspond to about 12 meters)

Let’s focus on the horizontal gradient in more detail (to be more precise – the modulus gradient of the total magnetic induction vector along the direction of the magnetometer motion). We have noted above that if each magnetometer is connected to a separate DigitalBottle connector on the Scan Fish, then when power is applied, the order and “mutual shift” of the magnetometer measurements along the time axis is set randomly with a *Constant Delays* between them (***Figure 4.1***). This was confirmed during the consultation with the EIVA specialist, the same is confirmed by ***Figure 4.3*** and ***Figure 4.4***.

Hence, when recording into an 8Mag-log file using a magnetometer-trigger, within a single “recording frame” the time shift between physical magnetometers’ measurements can be as long as a period of measurements. The most common period value is 0.1 seconds. At a vessel speed of 5 knots, a time of 0.1 second would correspond to 0.25 meters. Thus, when recording into the 8Mag-log file, the vertical gradient calculated by two magnetometers will contain:

1) The vertical gradient component on the gradiometric base of 0.5 meters (the usual distance between magnetometers for a Scan Fish);
2) The horizontal gradient component on a random gradiometric base from 0 to 0.25 meters, being constant along the entire survey profile. The component value will change only after Scan Fish power is turned on/off or when the recording time is very long due to the frequency mismatch of other magnetometers with the magnetometer-trigger in the seventh digit (see the long-period trend for Constant Delay in ***Figure 4.3***).

A value of 0.25 meters is large enough to be compared with 0.5 meters, while the magnitude of the horizontal gradient here will contribute significantly to the results of the difference between the measurements of the two magnetometers. ***Figure 7.1*** shows exactly such a case:

-- The red and yellow plots are characterized by a small-time Constant Delay (the delay between the magnetometers' measurements from which the vertical gradient is calculated) with a weak physical vertical gradient;

-- The green plot is characterized by a significant Constant Delay in time between the magnetometers' measurements with a weak physical vertical gradient. The plot is mainly determined by the magnitude of the horizontal gradient caused by the time delay between the magnetometer measurements;

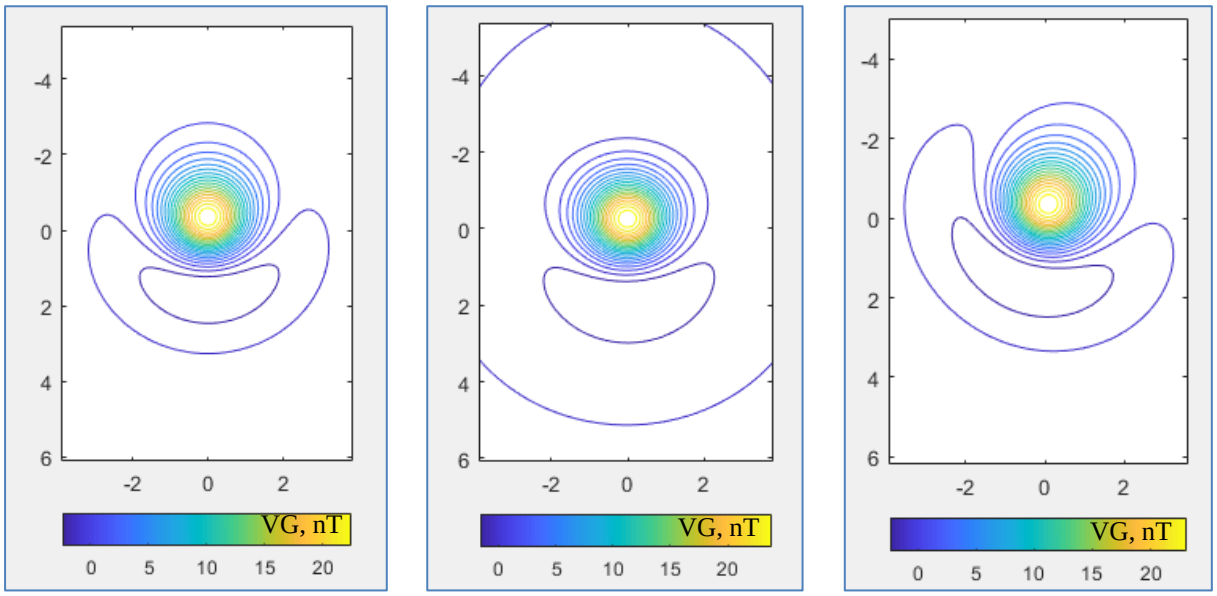
-- The blue plot is also characterized by a significant time of Constant Delay between magnetometer measurements. Contrary to the green plot, the time of one of the two magnetometers (from which the gradient is calculated) periodically "jumps" over the time of the magnetometer-trigger, which produces the saw-effect. Due to this "jumping", the horizontal gradient "changes its sign", resulting in a plot shape similar to modulated high frequency oscillation.

The intermediate conclusions to be recorded into the 8Mag-log file using a magnetometer-trigger:

1) Magnetic field anomalies are the sum of a vertical gradient and a horizontal gradient on a random base from 0 to ~50% of the vertical gradient base. In extreme cases, the recorded VG anomaly can be completely determined by the horizontal gradient (***Figure 7.1***, green plot).
2) When the Scan Fish passes over the magnetic anomaly again, the magnetic field plots will slightly differ due to the change of the horizontal gradient random component. That is, the "non-repeatability" of measurements for the same location is already inherent in the measurement method proper.
3) Strictly speaking, the object parameters responsible for the magnetic anomaly can be estimated inaccurately in such measurements because of the anomaly shape distortion. Here we are not discussing a need "to identify the quality object presence". Rather, it is the solution of the inverse geophysical problem and selection of characteristics of magnetically active masses that we are talking about.

Let's estimate the Constant Delay effect on the VG anomalies shape of potential UXO, based on the results of modeling done for geographic coordinates [53N, 2E] (parameters for the normal magnetic field by IGRF: 49540 nT, declination 1.44 degrees, inclination 67.81 degrees). Let's think of a magnetically perturbing body in a ball form with a radius of 0.1 meter and a magnetic susceptibility of 100 (iron). Let this body have only induction magnetization and no anisotropy and demagnetization effects; then such an object will produce an anomaly corresponding to a magnetic dipole.

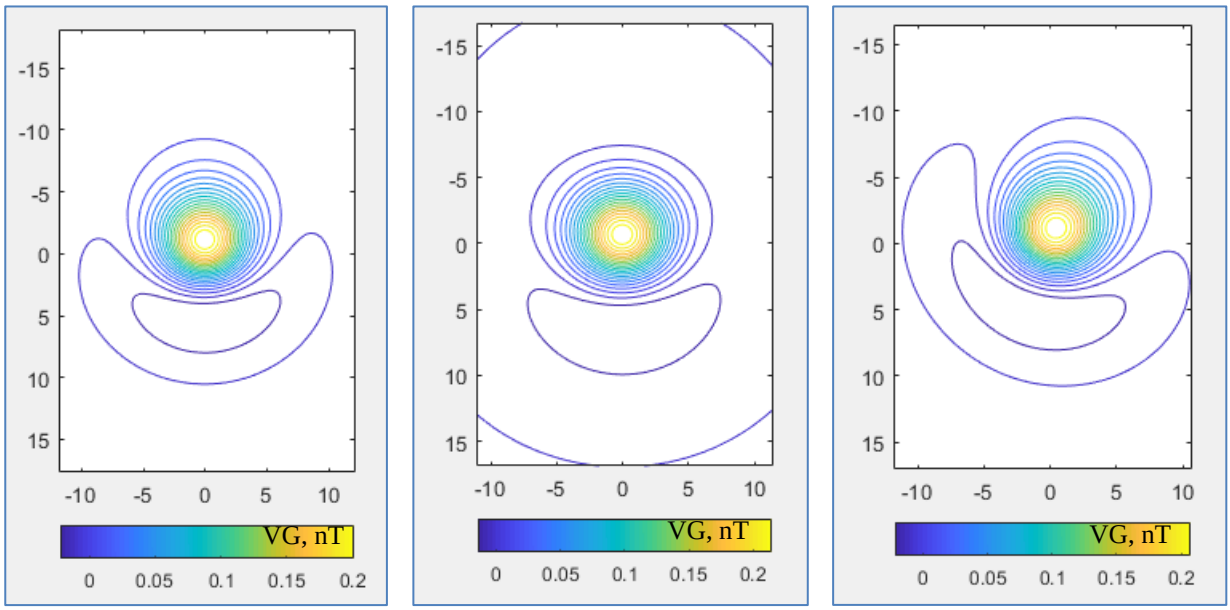
Let's calculate the VG anomaly for the height of the magnetometers above the object equal to 2 and 2.5 meters (***Figure 7.2***, a). After that, we are modeling the Constant Delay for the upper magnetometers (actually, just shift the field calculated for 2.5 meters) to 0.2 meters. We will model the delay as if the survey lines were in the N-E and E-W directions (***Figure 7.2***, b-c).



(a) no delay (b) N-S delay 0.2m (c) E-W delay 0.2m

Figure 7.2 The VG anomaly for heights of 2 and 2.5 meters at the Constant Delay of the upper magnetometer measurements by 0.2 meters; axes in meters, color scale in nT

Let's perform the same calculations for VG when the height of magnetometers above the object is 7 and 7.5 meters (***Figure 7.3***).



(a) no delay (b) N-S delay 0.2m (c) E-W delay 0.2m

Figure 7.3 VG anomaly for heights of 7 and 7.5 meters at the Constant Delay of the upper magnetometer measurements by 0.2 meters; axes in meters, color scale in nT

The analysis of ***Figure 7.2*** and ***Figure 7.3*** enable us to draw the following conclusions for the magnetic dipole field: (1) the magnetic anomaly VG is deformed, but retains its shape in the first approximation; (2) the shift of the anomaly maximum does not exceed 1 meter.

When surveying on the opposite survey lines with a constant delay of the upper magnetometer measurements, the anomaly will have characteristic “puffs” in the direction of the survey profiles (***Figure 7.4***).

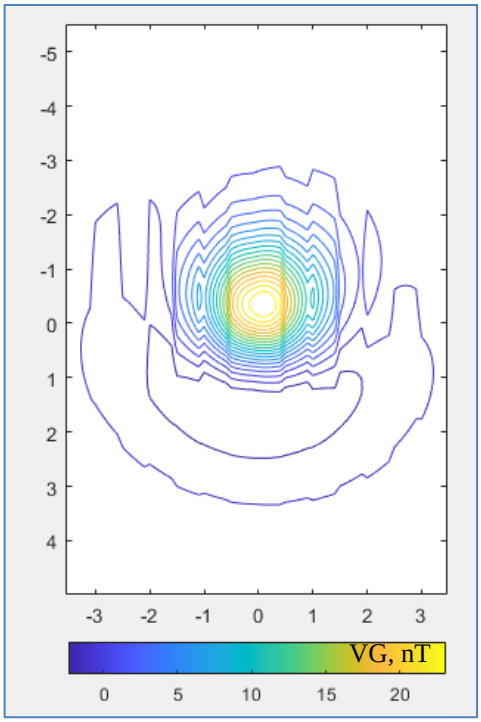


Figure 7.4 The VG anomaly for heights of 2 and 2.5 meters at constant delay of the upper magnetometer measurements when surveying on the opposite survey lines; axes in meters, color scale in nT

The regularities described above are also preserved in the presence of the residual magnetization component of the dipole. Thus, when recording into the 8Mag-log file by using a magnetometer-trigger, the magnetic field of the dipole in the depth range of the potential UXO can be “deformed”, but it will retain its shape and position of the anomaly maxima in the first approximation.

Conclusion

Recording measurements of magnetometers with Scan Fish poses a problem because QINSy does not record the time of measurement as such, it registers the time of data arrival to QINSy. Accordingly, delays in the data transmission channel bring about data arrival time delays and even skipping magnetometer data for the current measurement of the "recording frame". Since QINSy repeats the previous values for the data skipped, this leads to magnetometers' "freezing" (***Figure 0.2***) and the appearance of *single spikes* on the vertical gradient of the magnetic field (when using 8Mag-log recordings for which one of the magnetometers is used as a trigger). If the number of single spikes is large, they form the ***saw-effect*** (***Figure 0.1***) on the recordings of the magnetic field vertical gradient.

Port-servers (***Table 1.1***), due to their individual characteristics, can lead to periodic data skipping (***Figure 3.1***), which also causes QINSy in the 8Mag-log to repeat the value of the previous measurement while single spikes are formed on the vertical gradient of the magnetic field.

The best settings of the measurement channel were chosen, which allow for the smallest spread of data arrival time in QINSy: UDP, no DataMon, 10Hz. This made it possible for us to move from the saw-effect in the 8Mag-log file to relatively rare single spikes (***Figure 3.5***). However, since with power supply the order of magnetometers' measurements is set at random, and the time interval between the measurements of different magnetometers is also random, the situations can arise when even a small spread leads to a saw-effect (***Figure 4.4***) due to the "unlucky" initial time of the magnetometer-trigger.

A complete solution to the problem lies in the ***algorithmic synchronization***, namely, a mathematical processing of the data arrival time in QINSy (in the simplest case, it is calculating the average value for the measurement arrival time; ***Figure 5.1***, ***Figure 5.2***), to bring it closer to the time of physical measurements (i.e., elimination of errors caused by delays in the data channel). It is more rational to record each magnetometer in 1Mag-log file with further off-line processing.

Additional conclusions not directly related to the saw-effect:

1) The lowest delay is characterized by the data channel with the following configuration: transmissions are performed via UDP protocol; the frequency of magnetometer measurements is 10Hz; DataMon is excluded from the data transmission chain.
2) The configuration described above in (1) allows the data with a measurement rate of 14 Hz to be logged into the 1Mag-log file, although the number of data skips increases as the current hardware accepts two consecutive measurement skips for PServ_2PS port server.
3) When each magnetometer is linked to a separate DigitalBottle connector, after the Scan Fish is power supplied, the order of measurements and data transmission from the magnetometers is set at random. The quartz clocks of magnetometers are not synchronized (like in G-882TVG) and actually perform measurements at different points in time. Lack of magnetometers' quartz synchronization also indicates that their measurement frequency slightly differs (long-period trend in ***Figure 4.3***).
4) The measurement system described in (3) results in a time difference for physical measurements on the two magnetometers from which the vertical gradient is calculated, which can be as small as 0.1 second

when using 8Mag-log (magnetometer-trigger). This delay will give 0.25 meters at a speed of 5 knots; as a consequence, the computed vertical gradient at a base of 0.5 meters will include a horizontal gradient component randomly between 0 and 0.25 meters. Algorithmic synchronization is likely to reduce the horizontal gradient base to a value of ±1-2 cm (this requires linearly interpolating the magnetic field values from the time the measurement was received in QINSy to the total time series for the 8 magnetometers).

5) To precisely synchronize the magnetometers used for gradient calculation, you can use a special Y-cable, the same as for G882TVG. The cables are available for connecting 2 and 4 magnetometers. The magnetometers connected to different Y-cables are recommended to be algorithmically synchronized. However, with algorithmic synchronization, a small difference is expected between measurements of systems using Y-cables and with separately connected magnetometers (the actual difference is assumed to be at the level of magnetic survey error).

Some comments for the future:

One should record the "measurement arrival time variation in QINSy" with one, two, three and four magnetometers linked to the port-server. This is the way to determine the impact of channel load on the measurement transmission delay. Based on the result obtained, we can draw an indirect conclusion regarding the delays for 1Mag-log files and the need to use Y-cables.

Appendix 1: Estimation of data transmission delay from magnetometers at different data channel settings

The appendix presents the time-steps' plots (which are calculated as plots of the difference between the arrival time of the previous and subsequent measurement into QINSy) for each of the magnetometers for Port Scan Fish and Starboard Scan Fish. The plots were drawn for different settings and configuration of the data channel. Measurements were performed at the seaport, Scan Fish was made on board the vessel, and QINSy and Data Mon were not "overloaded" with extra tasks.

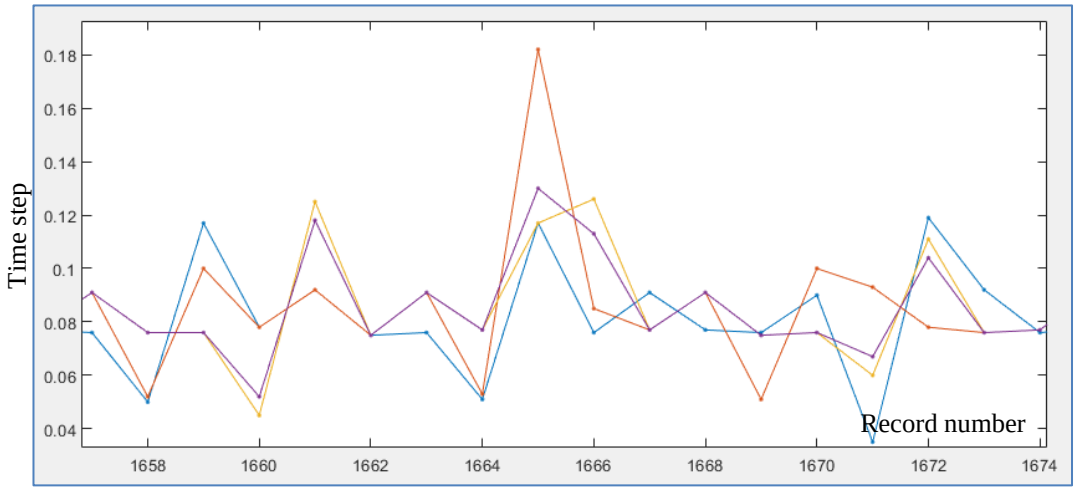
The horizontal axis represents the time when the measurement arrives at QINSy. The vertical axis shows the time-step which is the difference of the arrival time between the current and the previous measurements. Thus, the plots also characterize the time delay of measurements' arriving at QINSy.

The right side of the pages contains the plots for which averaging of the arrival time has been performed in a sliding window for 11 points. Such plots serve two purposes:

-- to estimate the extent of data arrival time spread reduction in QINSy upon averaging;

-- to identify skips in the data against the large data spread.

Let's explain the second point. The figure below shows what a missed measurement looks like against a large spread of data. As a result of several harmonics superposition, the data skip on the three magnetometers does not stand out as a high-amplitude single outlier (spike), but just two consecutive values with a "relatively high amplitude" that does not exceed the background data spread. To visually "highlight" the missed measurement, we can perform averaging in a sliding window. If we use the same weights within the window, the missing value will be highlighted as a meander, i.e., a rectangular pulse with a width equal to that of the sliding window. Meanwhile, the amplitude of a single spike will decrease proportionally to the width of the sliding window.



An example of time-steps before and after averaging in a sliding window is shown below.

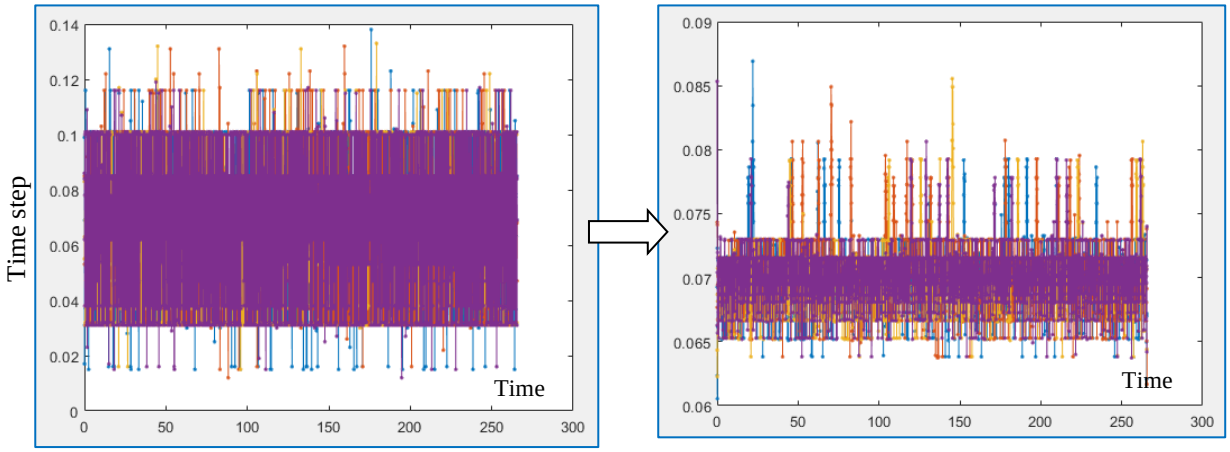


Figure title code used in Appendix 1:

N_PPP_FFF_SF-MMM-baudrate

examples: 1_COM_14Hz_PS-Mon, 4_UDP_14Hz_SB

where:

N – a serial measurement number (to simplify the reference search);

PPP – type of data transmission protocol (Real Com or UDP);

FFF – magnetometer measurement frequency (10Hz, 12Hz or 14Hz);

SF – Scan Fish code (PS – port side, SB – starboard side);

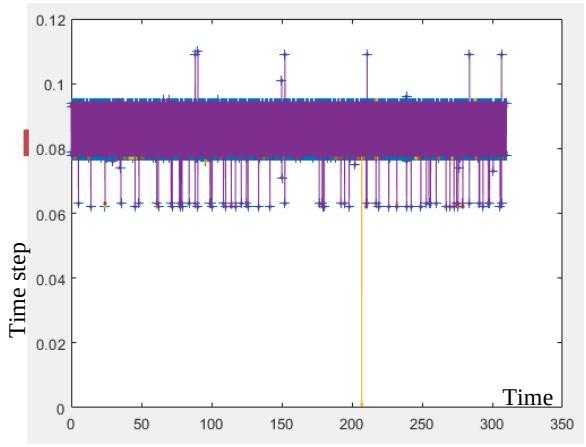
MMM – use of DataMon (Mon – data flow is transmitted through DataMon, empty – data flow is transmitted to QINSy directly from TopsideUnit, Switch – data flow is separately transmitted through Switch to QINSy and DataMon);

baudrate – for all measurements the port-server communication rate (and data flow rate for each magnetometer) was set to 9600 baud except for 15 and 17, when it was set to 19200 baud.

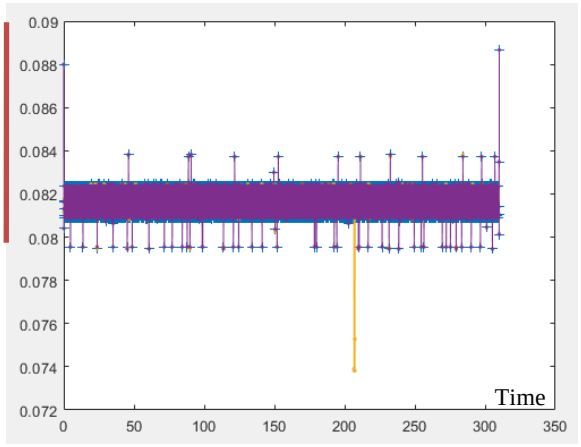
Measurements were performed for Port Scan Fish and Starboard Scan Fish simultaneously with different Scan Fish configurations. Simultaneous measurements are placed within one page in Appendix 1.

The red line on the left side of the figures shows the value of 0.01 second for convenience of comparing vertical scales.

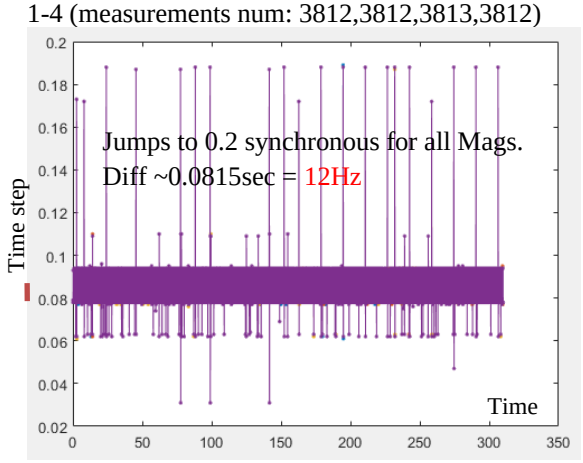
1_COM_14Hz_PS-Mon (in a fact 12Hz) – RealCom cannot be used for >10Hz



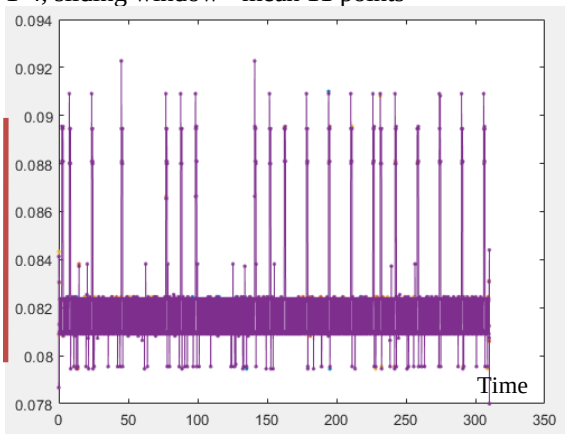
1-4 (measurements num: 3812,3812,3813,3812)



1-4, sliding window - mean 11 points

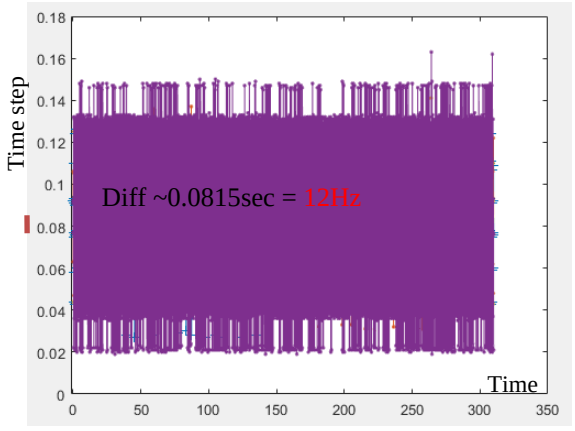


5-8 (measurements num: 3792,3792,3792,3792)

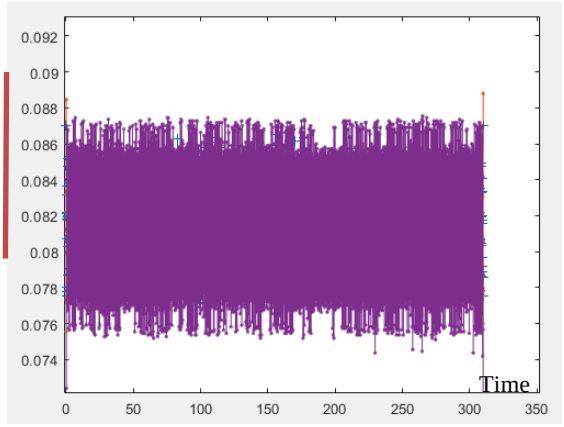


5-8, sliding window - mean 11 points

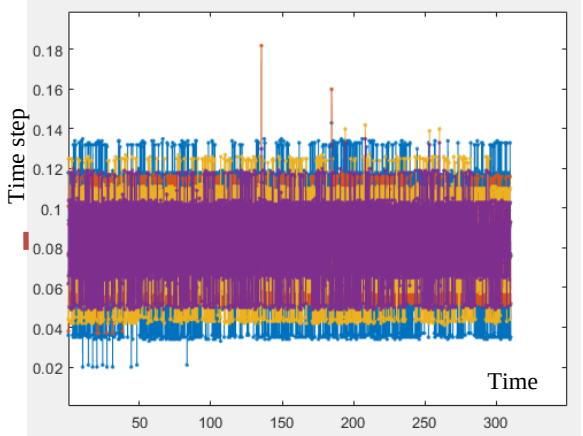
2_COM_14Hz_SB (in a fact 12 Hz) – RealCom cannot be used for >10Hz



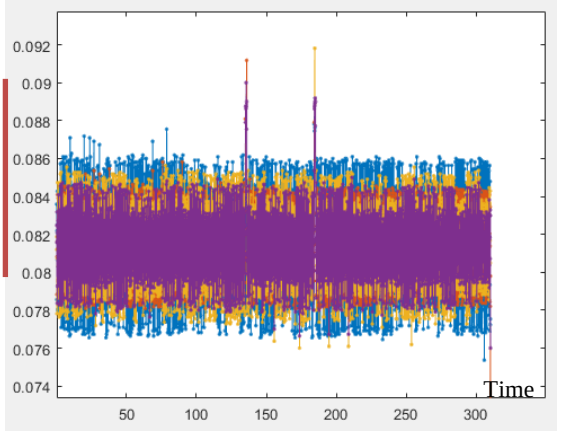
1-4 (measurements num: 3812,3812,3812,3812)



1-4, sliding window - mean 11 points

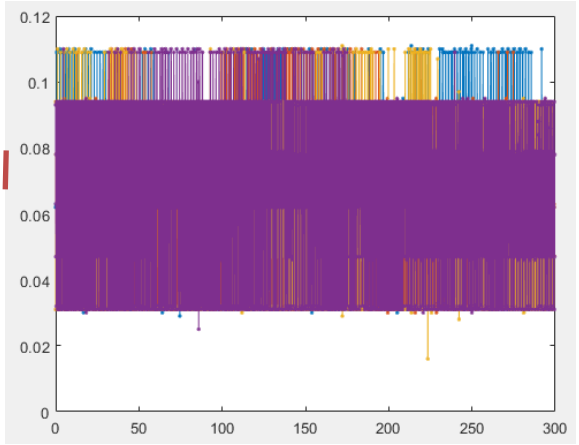


5-8 (measurements num: *3811*,3810,3810,3810)

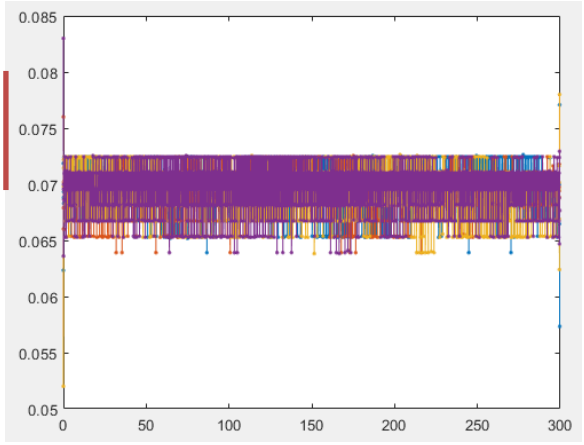


5-8, sliding window - mean 11 points

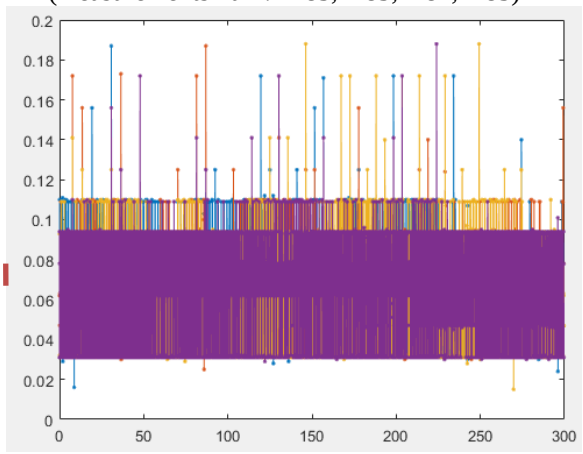
3_UDP_14Hz_PS-Mon



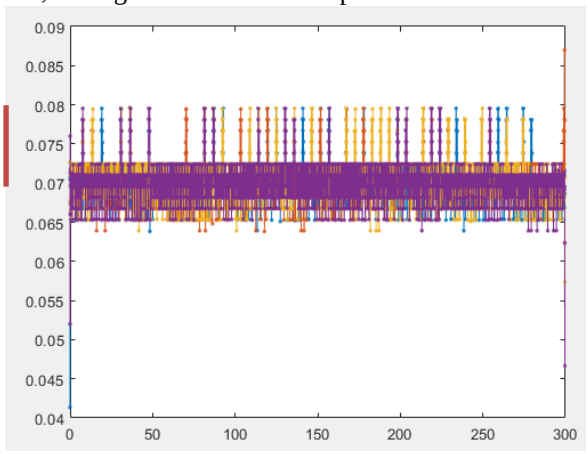
1-4 (measurements num: 4283,4283,4282,4283)



1-4, sliding window - mean 11 points

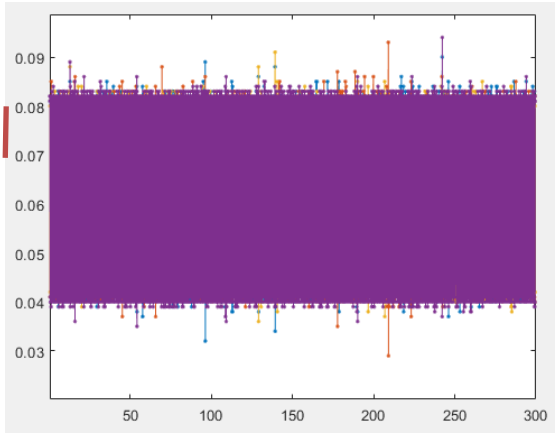


5-8 (measurements num: 4264,4264,4260,4268)

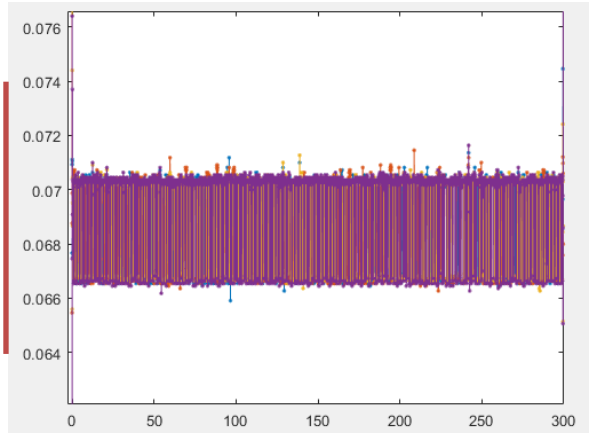


5-8, sliding window - mean 11 points

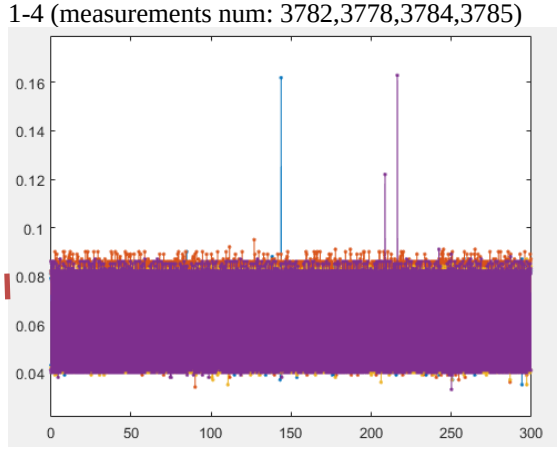
4_UDP_14Hz_SB



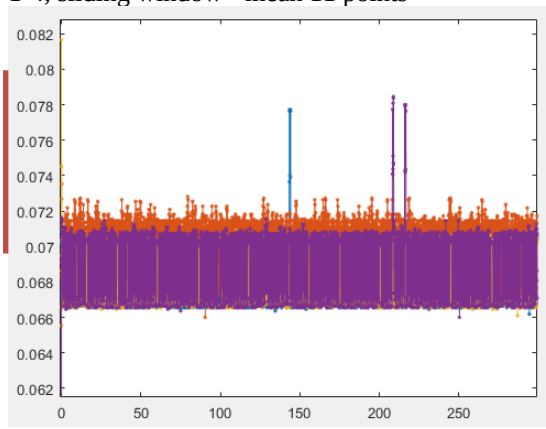
1-4 (measurements num: 3782,3778,3784,3785)



1-4, sliding window - mean 11 points

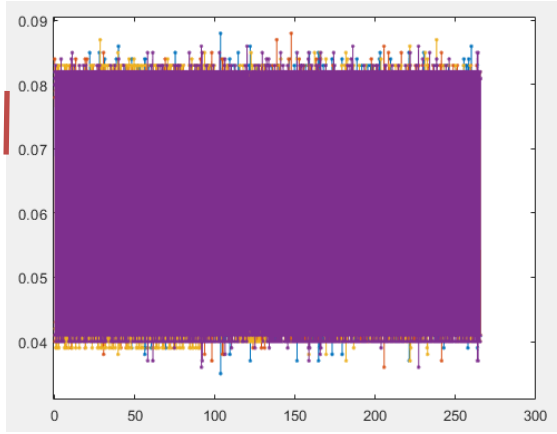


5-8 (measurements num: *3785*,3790,3777,3781)

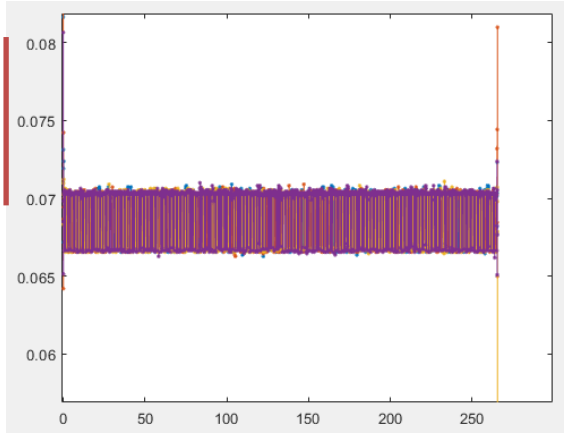


5-8, sliding window - mean 11 points

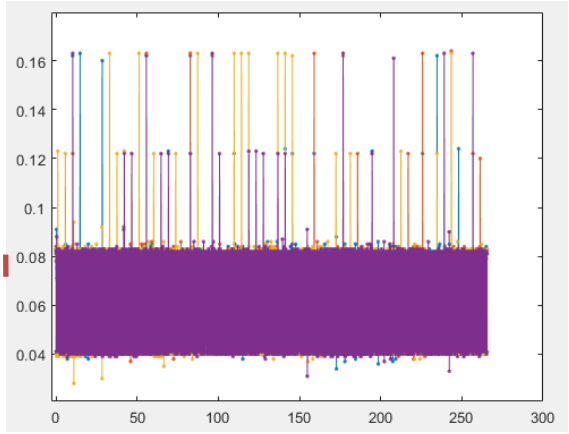
5_UDP_14Hz_PS



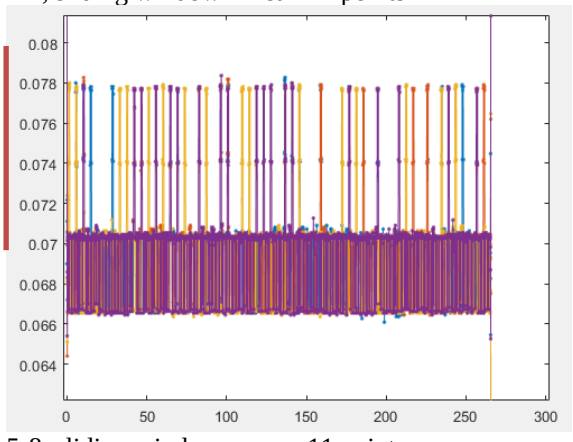
1-4 (measurements num: 3796,3796,3796,3795)



1-4, sliding window - mean 11 points

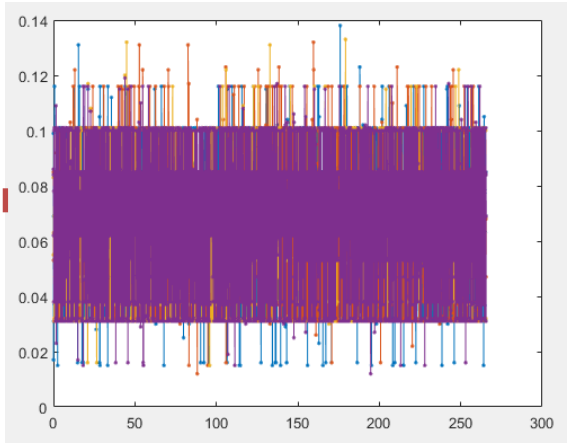


5-8 (measurements num: 3775,3779,3774,3777)

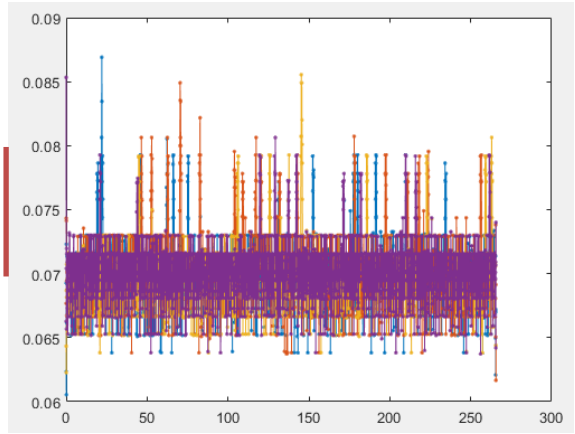


5-8, sliding window - mean 11 points

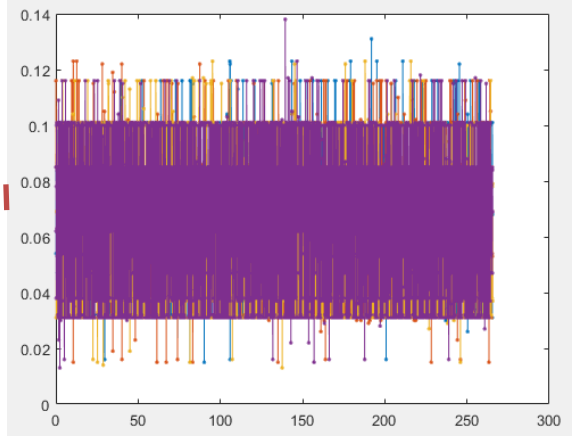
6_UDP_14Hz_SB-Mon



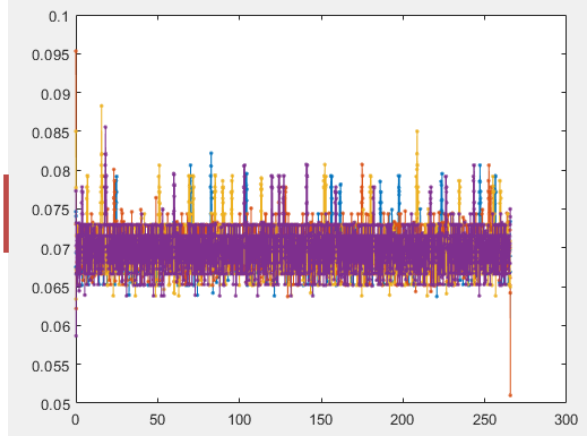
1-4 (measurements num: 3782,3778,3784,3785)



1-4, sliding window - mean 11 points

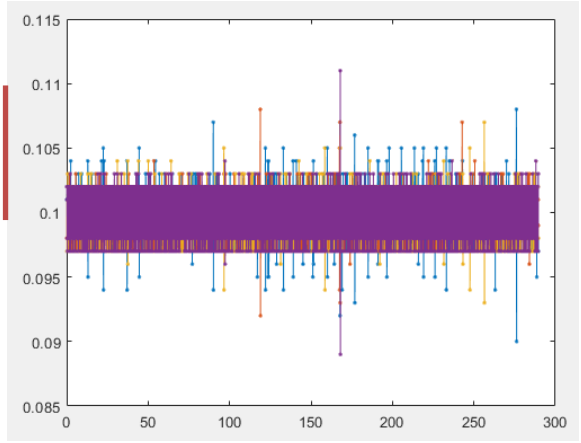


5-8 (measurements num: *3785*,3790,3777,3781)

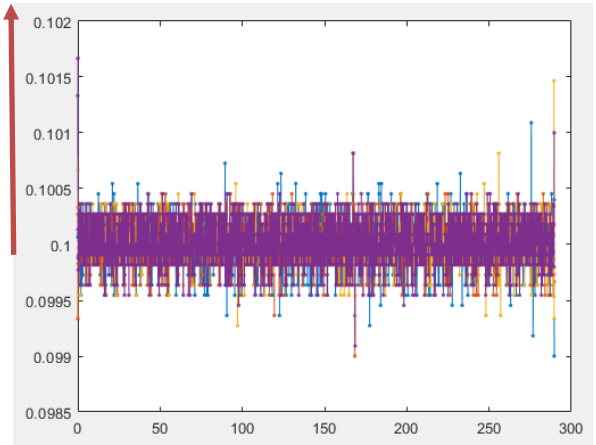


5-8, sliding window - mean 11 points

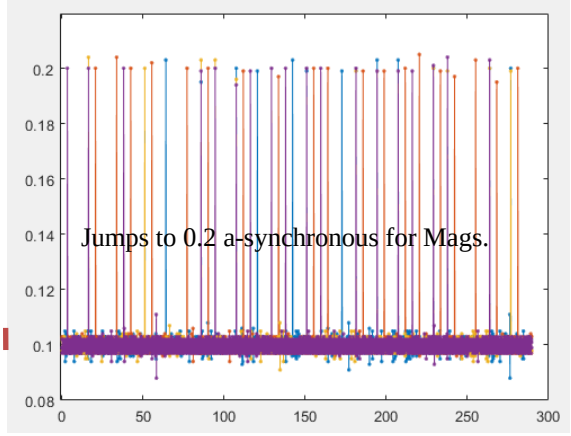
7_UDP_10Hz_PS



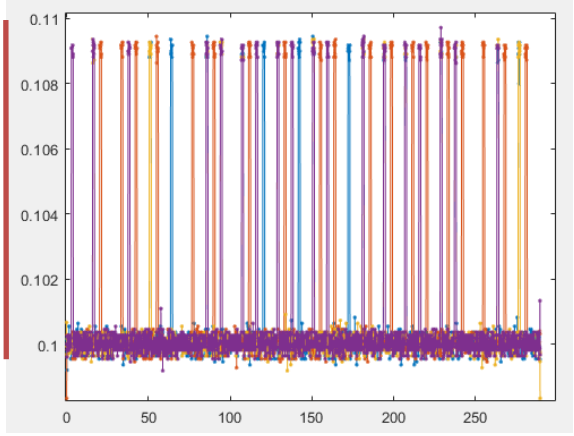
1-4 (measurements num: 2898,2897,2897,2897)



1-4, sliding window - mean 11 points

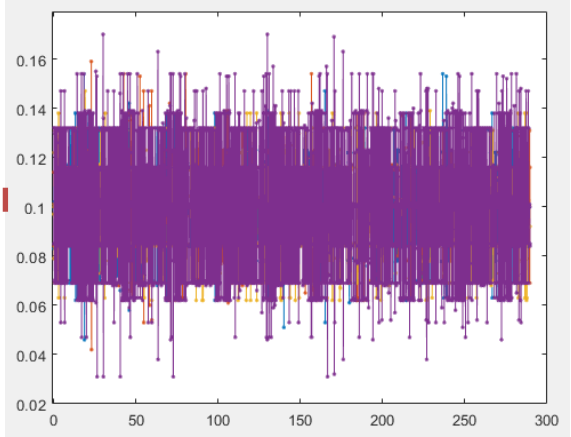


5-8 (measurements num: 2883,2879,2884,2879)

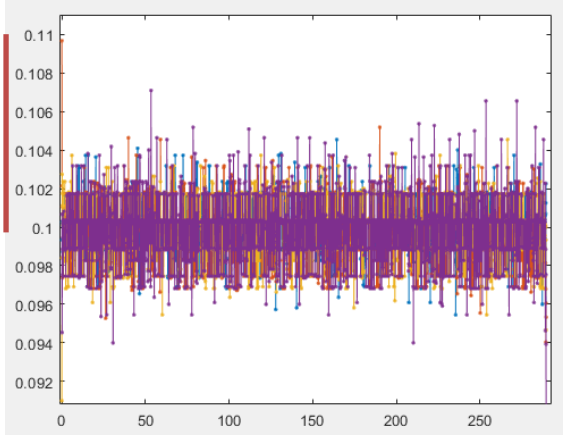


5-8, sliding window - mean 11 points

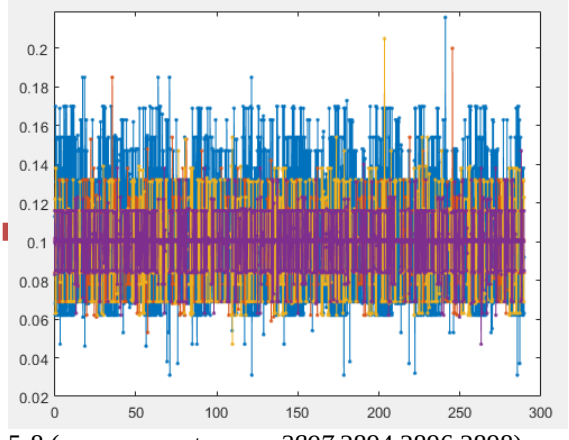
8_UDP_10Hz_SB-Mon



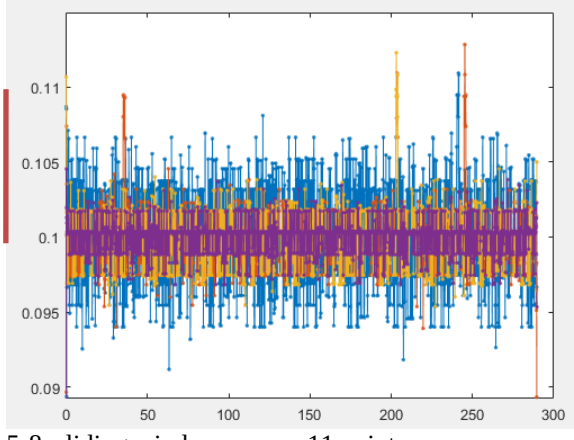
1-4 (measurements num: 2898,2898,2898,2898)



1-4, sliding window - mean 11 points

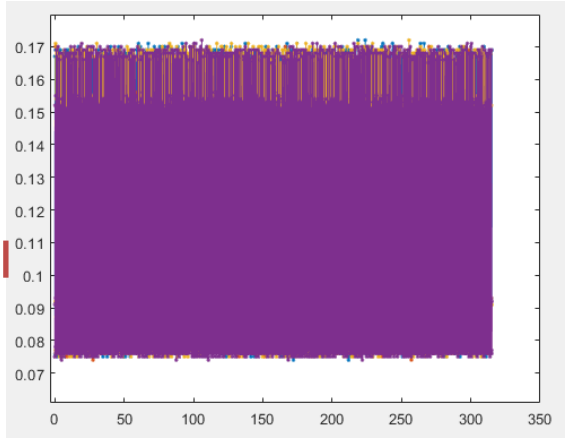


5-8 (measurements num: *2897*,2894,2896,2898)

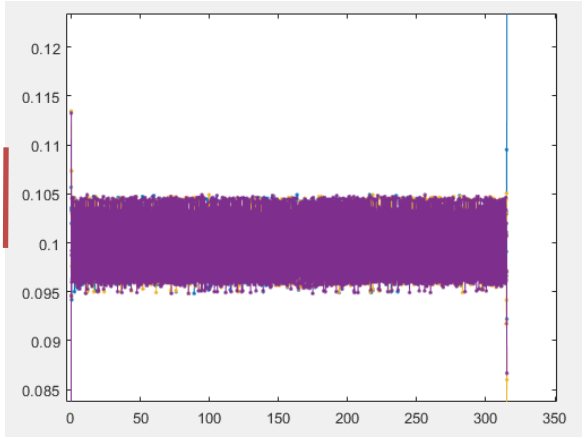


5-8, sliding window - mean 11 points

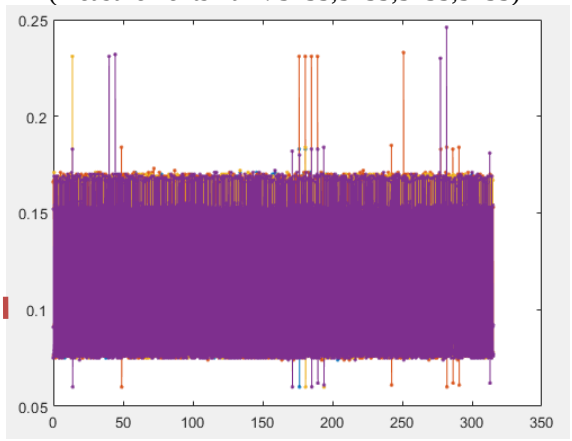
9_COM_10Hz_PS



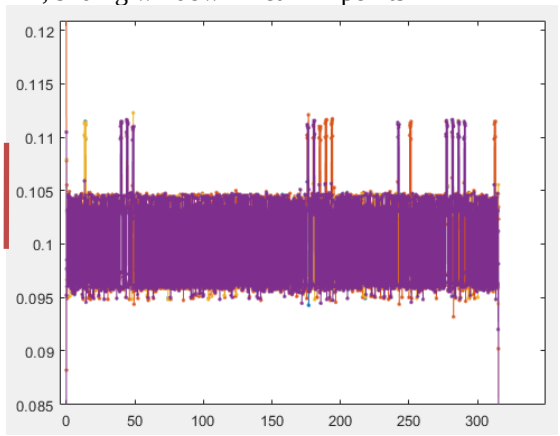
1-4 (measurements num: 3155,3155,3155,3155)



1-4, sliding window - mean 11 points

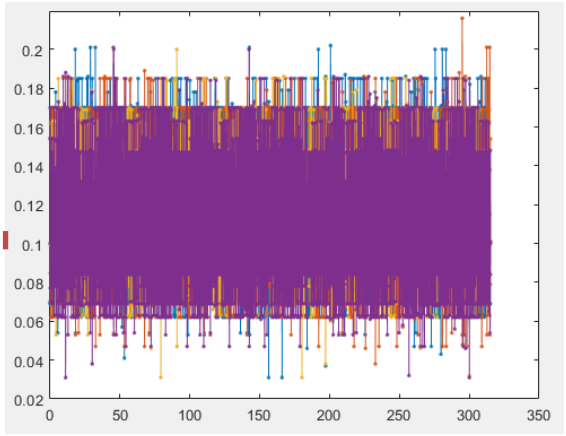


5-8 (measurements num: 3146,3144,3145,3145)

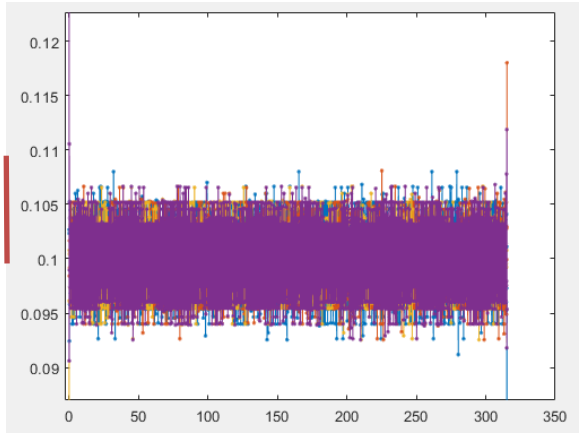


5-8, sliding window - mean 11 points

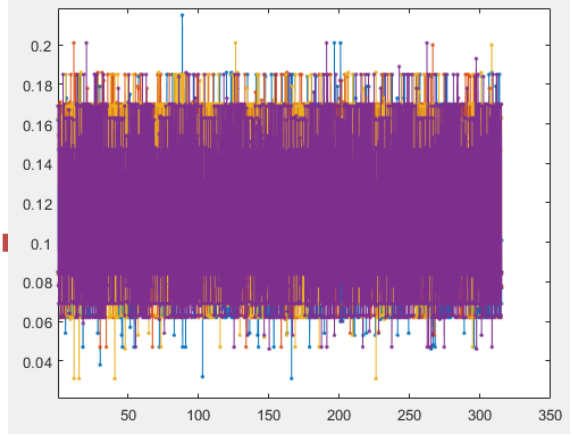
10_COM_10Hz_SB-Mon



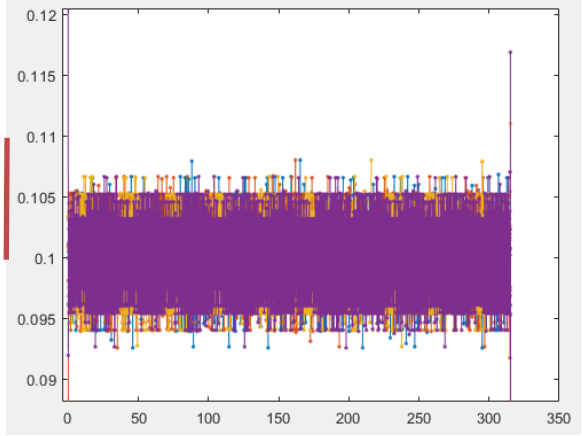
1-4 (measurements num: 3155,3155,3155,31255)



1-4, sliding window - mean 11 points

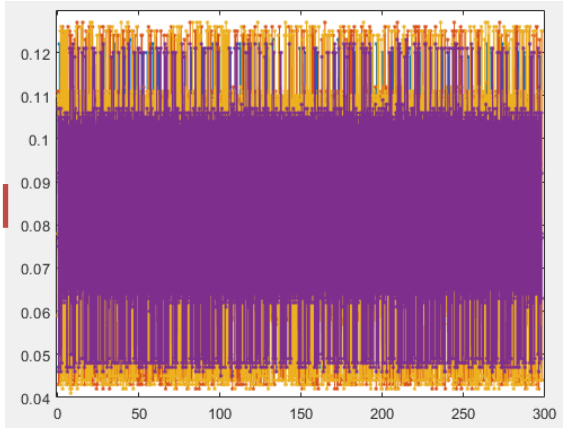


5-8 (measurements num: *3155*,3155,3155,3156)

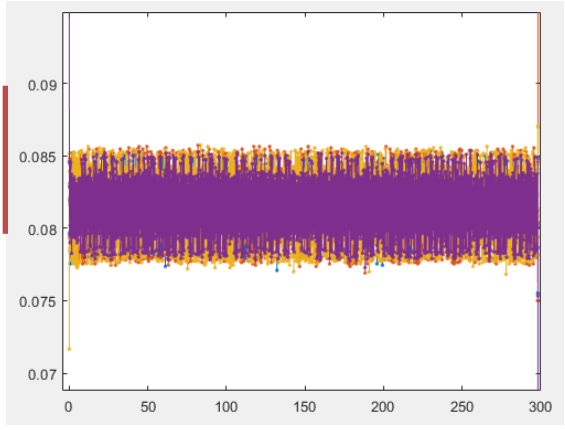


5-8, sliding window - mean 11 points

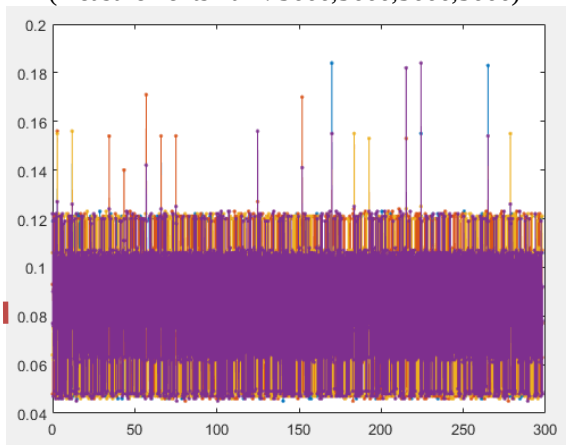
11_COM_12Hz_PS



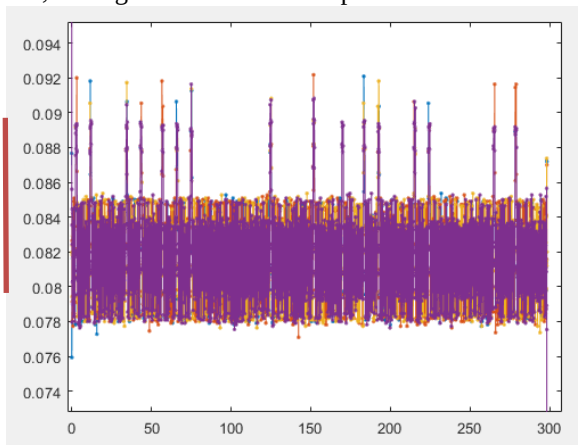
1-4 (measurements num: 3666,3666,3666,3666)



1-4, sliding window - mean 11 points

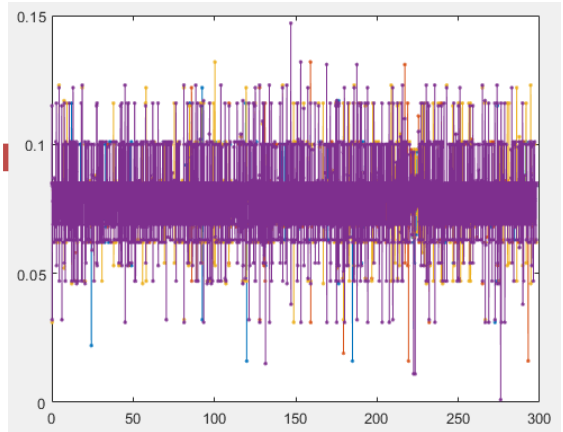


5-8 (measurements num: 3650,3650,3145,3145)

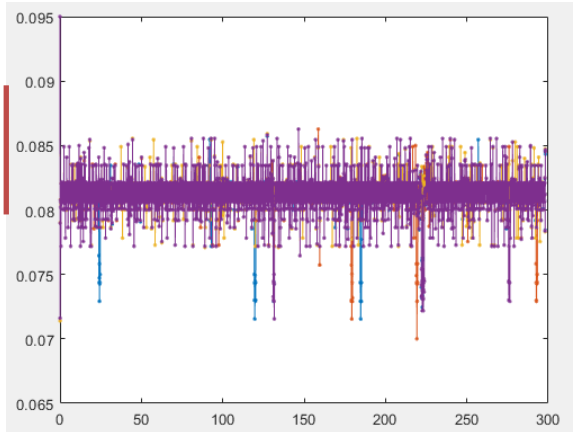


5-8, sliding window - mean 11 points

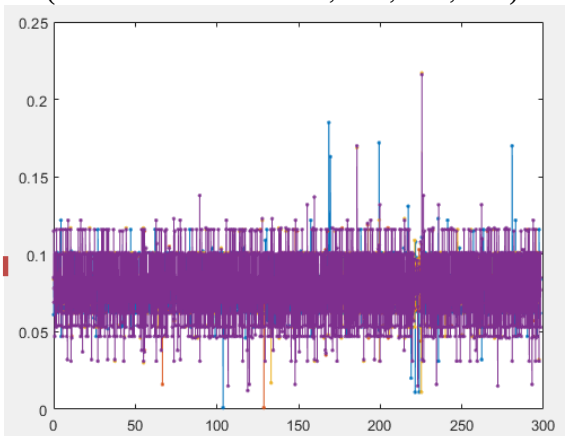
12_COM_12Hz_SB-Mon



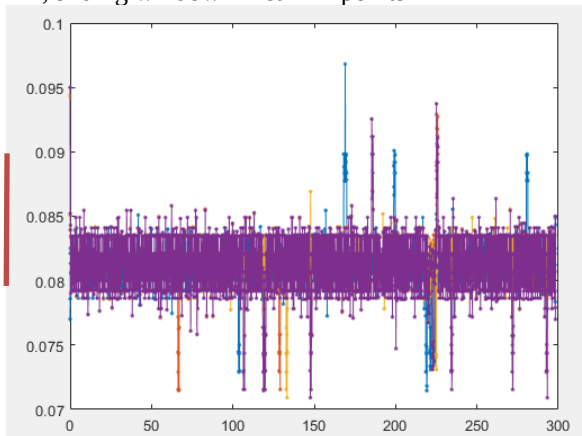
1-4 (measurements num: 3672,3670,3676,3671)



1-4, sliding window - mean 11 points

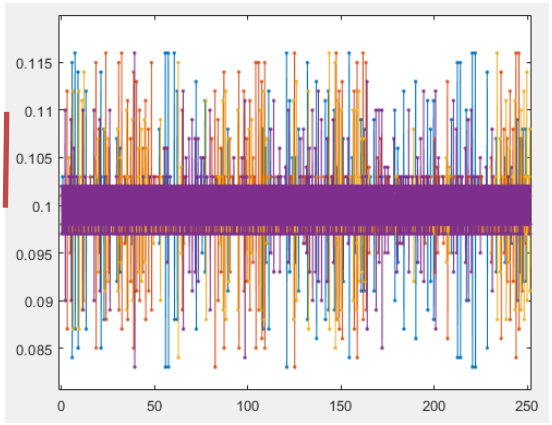


5-8 (measurements num: *3667*,3667,3667,3673)

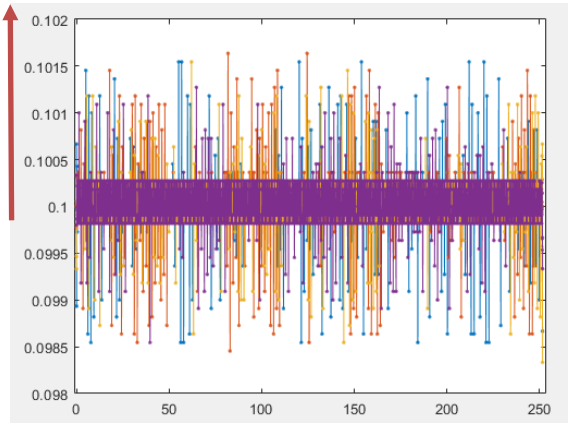


5-8, sliding window - mean 11 points

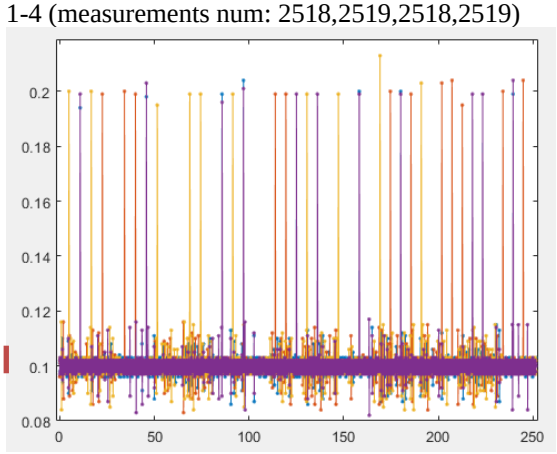
13_UDP_10Hz_PS-Switch



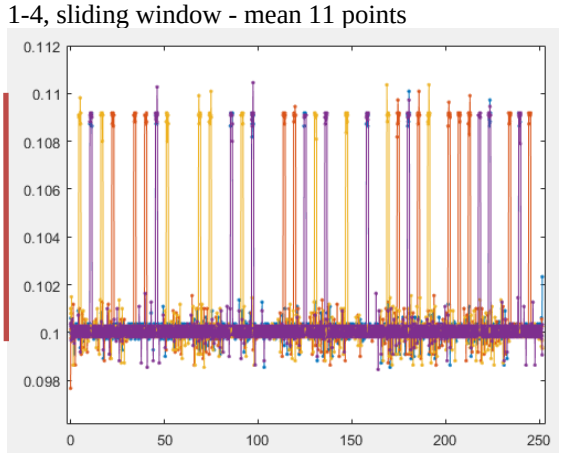
1-4 (measurements num: 2518,2519,2518,2519)



1-4, sliding window - mean 11 points

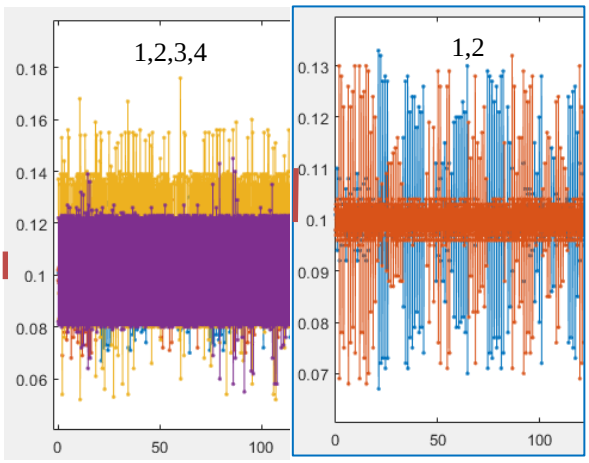


5-8 (measurements num: 2510,2507,2508,2508)

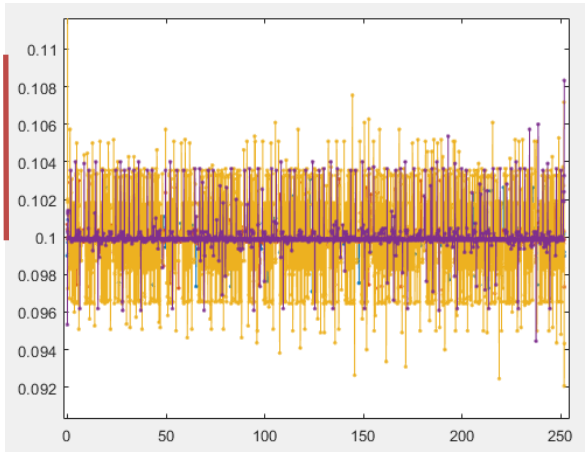


5-8, sliding window - mean 11 points

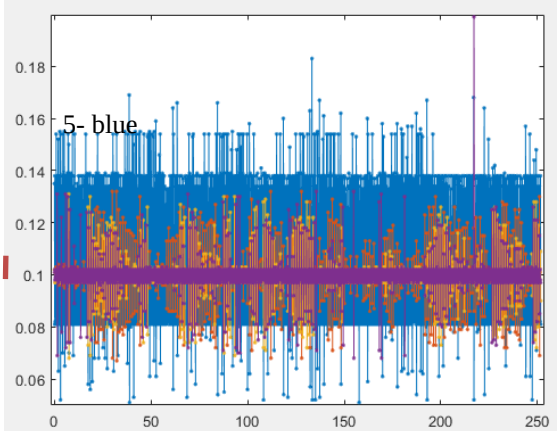
14_UDP_10Hz_SB-Switch



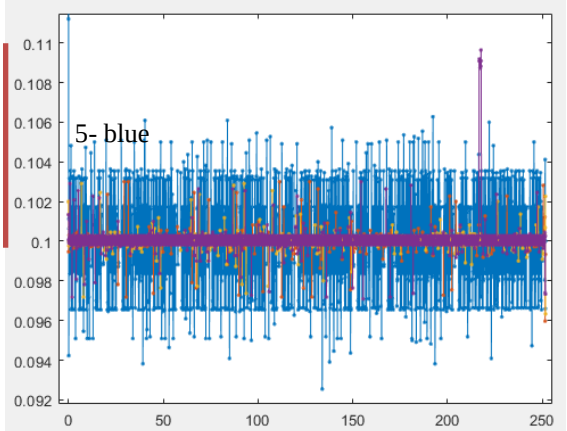
1-4 (measurements num: 2518,2519,2518,2518)



1-4, sliding window - mean 11 points

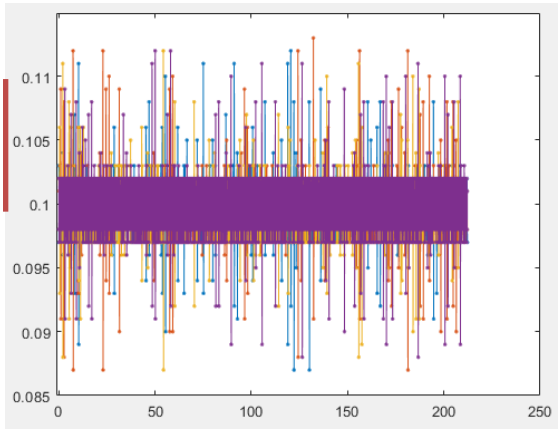


5-8 (measurements num: *2519*,2518,2519,2517)

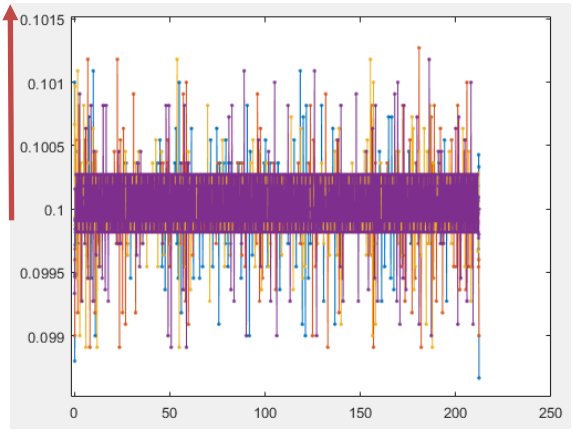


5-8, sliding window - mean 11 points

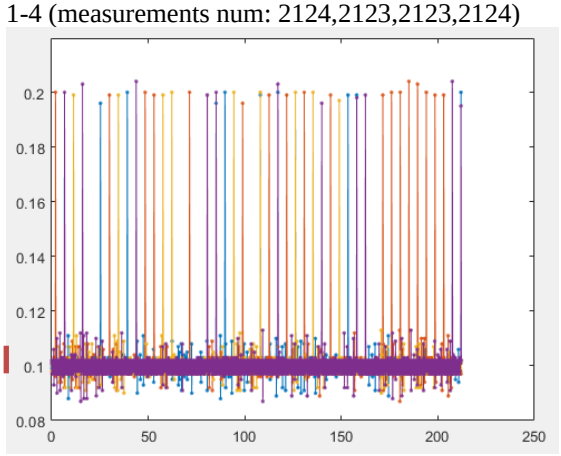
15_UDP_10Hz_PS-Switch-19200



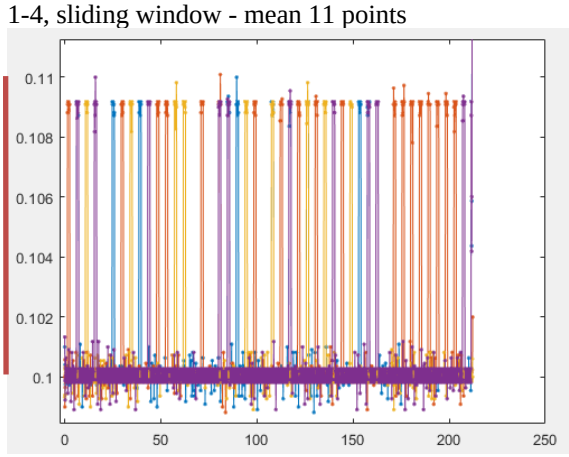
1-4 (measurements num: 2124,2123,2123,2124)



1-4, sliding window - mean 11 points

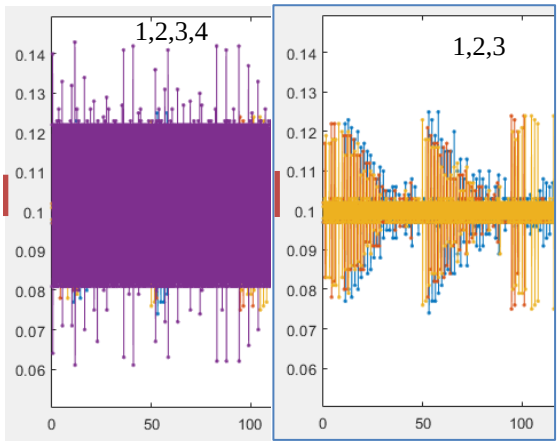


5-8 (measurements num: 2112,2105,2114,2112)

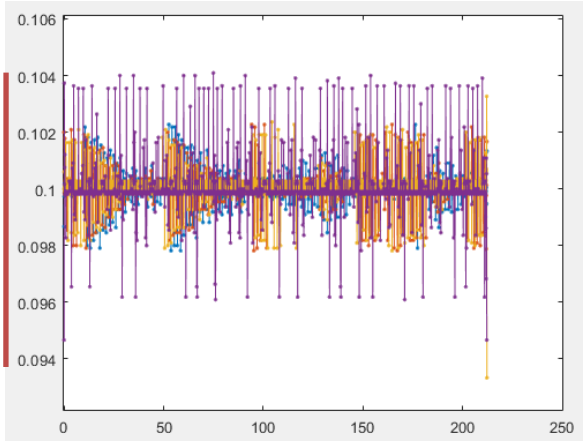


5-8, sliding window - mean 11 points

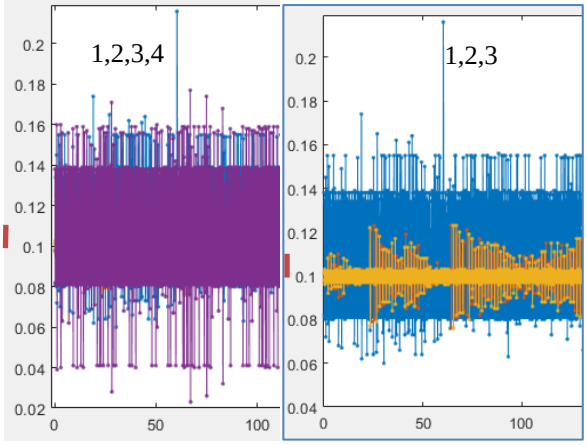
16_UDP_10Hz_SB-Switch



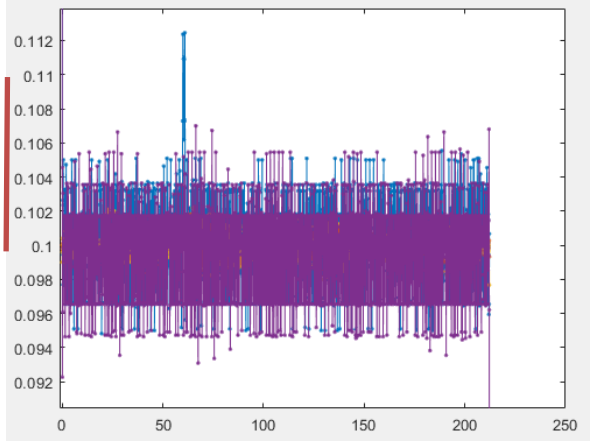
1-4 (measurements num: 2124,2124,2124,2123)



1-4, sliding window - mean 11 points

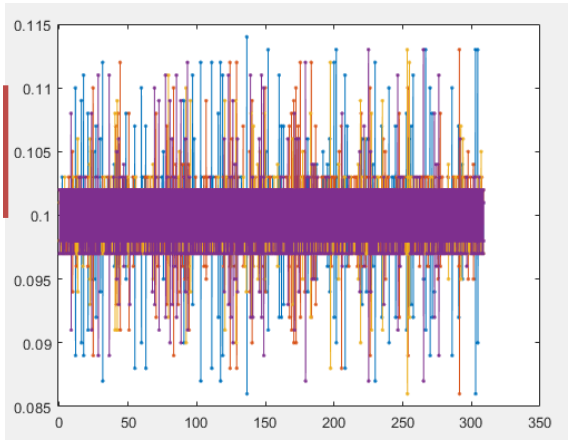


5-8 (measurements num: *2122*,2124,2124,2124)

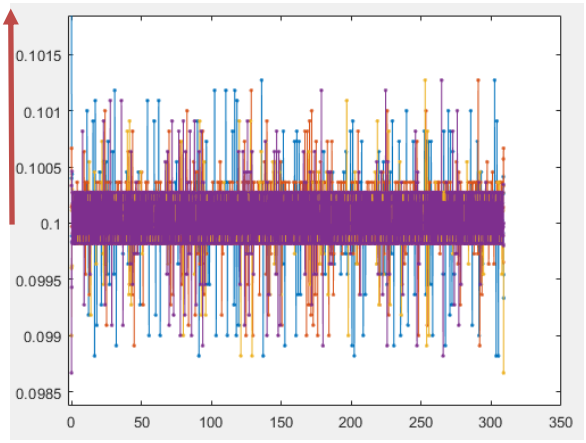


5-8, sliding window - mean 11 points

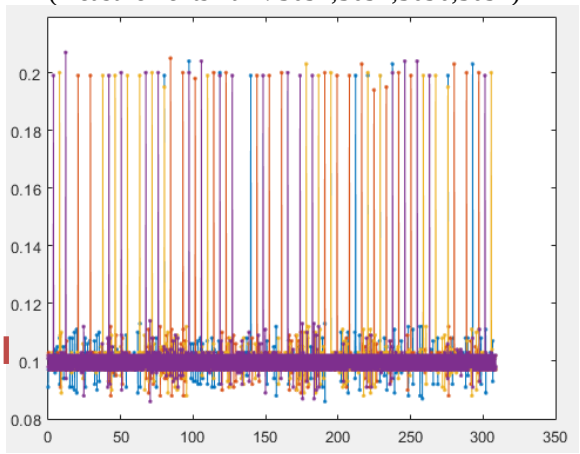
17_COM_10Hz_PS-Switch-19200



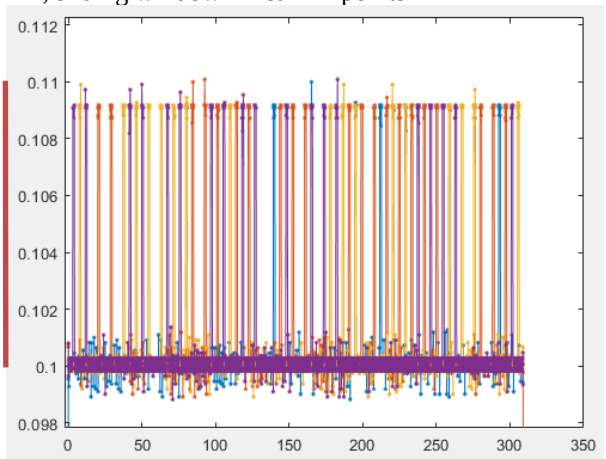
1-4 (measurements num: 3091,3091,3090,3091)



1-4, sliding window - mean 11 points



5-8 (measurements num: 3077,3069,3073,3072)



5-8, sliding window - mean 11 points