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Analysis of Orbit Response Matrices for Optics Correction with the Gradient Dipole Trim Coils at Alba

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Abstract

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The aim of this project is: firstly, to evaluate how the combined function dipole's gradient errors vary along time. In order to do so, data acquired during two years by the ALBA team have been analysed. This has been done by calculating the trim coils' strength to be applied to correct the gradient error; secondly, performing simulations to obtain the the horizontal corrector magnets' strength change and performing simulations of the combined function dipole's realignment - horizontal shifts - so as to keep the beam orbit unchanged. The matrices analysis have been performed using the MATLAB's LOCO mode. MATLAB scripts have been written to perform the gradient's strength changes calculation.

Moreover, the simulations of the beam's orbit correction have been performed with the MATLAB Accelerator Toolbox (AT) and the MATLAB Middle Layer library (MML).

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ANALYSIS OF ORBIT RESPONSE MATRICES FOR
OPTICS CORRECTION WITH THE GRADIENT
DIPOLE TRIM COILS AT ALBA

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1 INTRODUCTION

The ALBA's storage ring consists of a magnetic structure employing different types of magnets. In the storage ring there are 112 quadrupoles and 32 combined function dipoles. Its optics is measured by analysing the orbit response matrix. To correct the storage ring's optics only quadrupole magnets are used, even though the combined function dipoles are also important sources of errors. In 2018, the optics correction has been upgraded by including 32 trim coils in the combined function dipoles, which were already installed but not powered yet. The trim coils allow individual powering to the dipoles.

The aim of this project is: firstly, to evaluate how the combined function dipole's gradient errors vary along time. In order to do so, data acquired during two years by the ALBA team have been analysed. This has been done by calculating the trim coils' strength to be applied to correct the gradient error; secondly, performing simulations to obtain the the horizontal corrector magnets' strength change and performing simulations of the combined function dipole's realignment - horizontal shifts - so as to keep the beam orbit unchanged. The matrices analysis have been performed using the MATLAB's LOCO code. MATLAB scripts have been written to perform the gradient's strength changes calculation. Moreover, the simulations of the beam's orbit correction have been performed with the MATLAB Accelerator Toolbox (AT) and the MATLAB Middle Layer library (MML).

2 THE PHYSICS OF ALBA'S SYNCHROTRON STORAGE RING

2.1 ALBA SYNCHROTRON

ALBA is a 3 GeV synchrotron light source operational since 2012 [1]. The accelerator complex (Fig. 2.1) has an injector, consisting of a 100 MeV linear accelerator (Linac), a 3 GeV booster ring, and the electron storage ring with a 368.8 m circumference [2]. There, the electron beam is employed to produce synchrotron radiation, which is used in the experimental beamlines to study matter at an atomic or subatomic scale and aslo for biological or chemical experiments. Currently, there are eight operational beamlines and three more are being built.

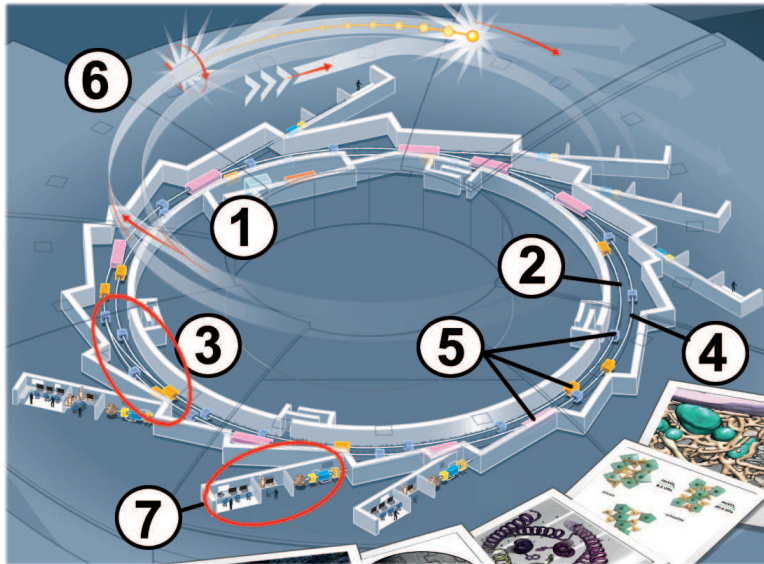


Figure 2.1: **ALBA SYNCHROTRON:** 1. LINAC 2. Booster 3. Transfer line (electrons go from the Booster to the Storage Ring) 4. Storage Ring 5. Magnets 6. Synchrotron light 7. Beamlines

2.2 MAGNETS IN A SYNCHROTRON

The arrangement of the different magnets in a storage ring – dipoles, quadrupoles, sextupoles... – is called magnetic lattice and it is designed differently depending on the purpose of the accelerator. The design orbit in a ring is defined by curves at the dipole sections and by straight sections where quadrupoles and other magnets are installed. In order to explain how the particles' trajectory changes throughout the different elements of the ring, the reference system will be defined as showed in Fig. 2.2.

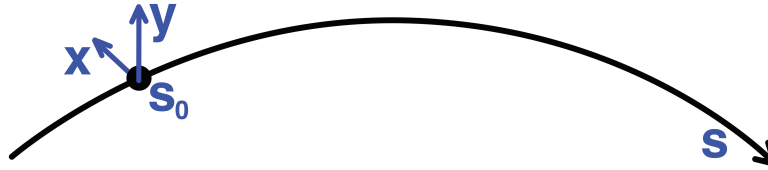


Figure 2.2: **Reference system:** the curvilinear coordinate s defines the position along the ring and a local reference system (x,y) defines the particle position in the transverse plane.

The types of magnets used in a synchrotron will now be explained.

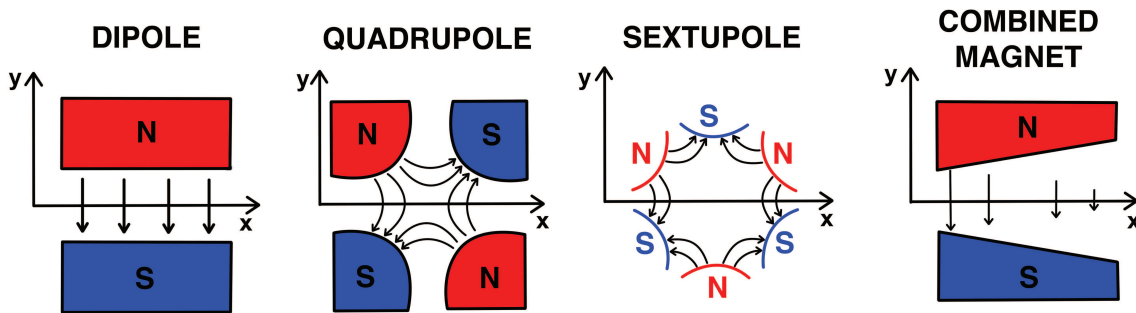


Figure 2.3: **Magnet types for a synchrotron:** Dipole, Quadrupole, Sextupole and combined magnet

The magnetic field for each magnet on the horizontal axis is illustrated in image 2.4

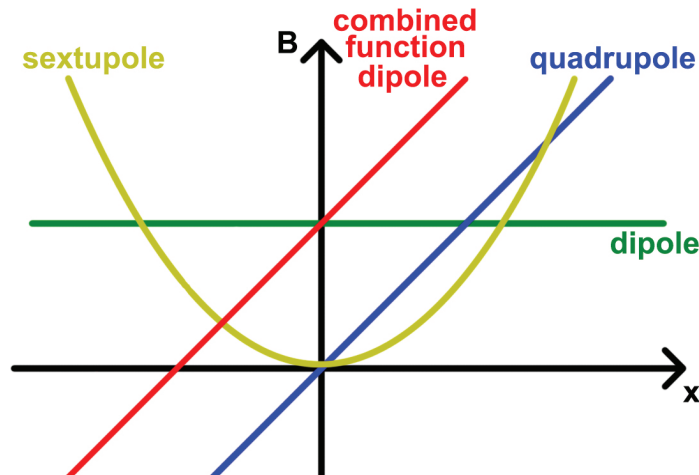


Figure 2.4: **Magnetic field of the different types of magnets as a function of the horizontal position x_0**

- **Dipole:** Dipoles are used to bend the electrons so that they follow a circular motion. Its field is defined by:

$$B_x = 0 \quad \text{and} \quad B_y = B_0 \quad (2.1)$$

A dipole with a uniform field bends the particle trajectory by an angle θ , as shown in Fig. 2.5

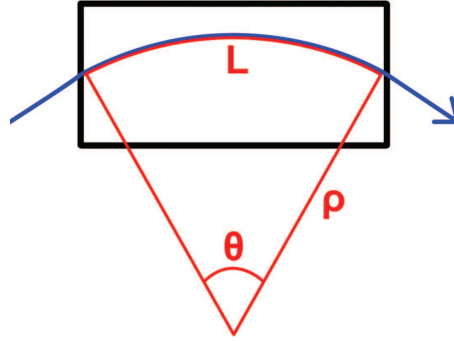


Figure 2.5: Trajectory of the beam through the dipole with a deflection angle θ

This angle depends on the dipole's length, L , its magnetic field, B , and the bending radius, ρ .

$$\theta = \frac{LB}{(B\rho)} \quad (2.2)$$

$B\rho$ is called **magnetic rigidity**:

$$B\rho = p/q \quad (2.3)$$

Where p is the particle momentum and q its charge. The magnetic rigidity measures a particle's resistance to deflection by a magnetic field. The higher the momentum and the lower the charge of the particle is, the higher is its resistance [3].

- **Quadrupole:** Quadrupoles are used for transverse focusing of the beam.

The field is zero at the centre and varies linearly with the transverse distance from it.

$$B_x = -Gy \quad \text{and} \quad B_y = Gx \quad (2.4)$$

Where the gradient G is $G = \frac{\partial B_y}{\partial x} \stackrel{\text{Maxwell}}{=} -\frac{\partial B_x}{\partial y}$ and the normalised focusing strength is $k = \frac{1}{B\rho} \frac{dB_y}{dx} [m^{-2}]$

In ALBA there are 112 quadrupoles installed in the Storage Ring.

- **Sextupoles:** Sextupoles are used to correct the lattice chromaticity, which is the focusing's dependence on momentum, and compensate unwanted non-linear magnetic fields.

In sextupoles the field varies quadratically with the displacement.

$$B_x = 2Sxy \quad \text{and} \quad B_y = S(x^2 - y^2) \quad (2.5)$$

Where S is $S = \frac{\partial^2 B_y}{\partial x^2}$ is the quadratic gradient that is constant.

In ALBA's storage ring's lattice there are 120 sextupoles.

- **Combined function Dipoles:** Combined function dipoles - or gradient dipoles - are magnets that combine dipolar and quadrupolar fields, which allows deflection and focusing of the beam at the same time. The usage of this type of magnets is useful to build a compact machine. An ALBA's combined function dipole is shown in Fig. 2.6 and it is described in more detail in Section 3.

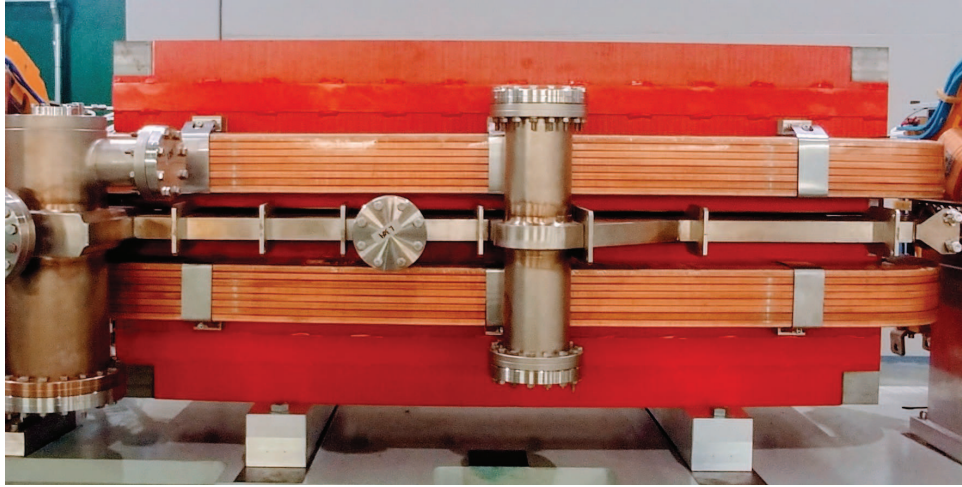


Figure 2.6: Combined function dipole magnet of ALBA synchrotron

Small orbit distortions are common in particle accelerators. They can be caused by finite precision in the magnets' fabrication and assembly, and also by misalignment when positioning them. These distortions can lead to beam loss by hitting the surrounding vacuum pipe. To prevent this, additional corrector dipoles are used.

- **Dipole corrector magnets:** They are small dipoles used to correct the orbit distortions produced by errors in the fields. They change the beam's orbit angle by giving the electrons a small kick. The change in the orbit's angle is described by:

$$\alpha = \frac{q}{p}Bl \tag{2.6}$$

Where B is the magnetic field and l is the length of the magnet.

In ALBA there are 88 horizontal dipole corrector magnets (HCM) and 88 vertical dipole corrector magnets (VCM), which are used to correct orbit displacements in both transverse planes, horizontal and vertical.

2.3 EQUATIONS OF TRANSVERSE MOTION

A detailed introduction to accelerator optics can be found in [3, 4, 5, 6, 7].

To describe the equations of motion it has to be taken into account that the motion of the particles is in the horizontal plane and its position is determined by the longitudinal coordinate s and the transverse x , y coordinates. Also, if $x, y \ll \rho$, the transverse motion is only due to the dipoles and quadrupoles, which have linear fields. The transverse motion can be described by the following equations:

$$x'' + k_x(s)x = \frac{1}{\rho} \frac{\Delta p}{p_0} \quad (2.7)$$

$$y'' + k_y(s)y = 0 \quad (2.8)$$

With

$$k_x = \frac{1}{\rho^2} + \frac{q}{p} \frac{\partial B_y}{\partial x} \quad k_y = -\frac{q}{p} \frac{\partial B_y}{\partial x} \quad (2.9)$$

Where ρ is the dipole's radius, p the momentum of the particles, p_0 is the nominal momentum of the particles, Δp is the momentum's difference from the nominal momentum particles, q the charge of the particles, B the magnetic field and x'' , y'' are the second derivatives with respect to s . Notice that k_x and k_y have opposite sign, a quadrupole focuses in one plane and defocuses in the other, this is why alternated focusing and defocusing quadrupoles are needed in an accelerator.

The solution of Eq.2.7 is the solution of the homogeneous equation plus a particular solution of the non-homogeneous equation:

$$x = x_{hom} + x_p \quad (2.10)$$

The solution of the non-homogeneous equation is proportional to $\frac{\Delta p}{p_0}$:

$$x_p(s) = D_x(s) \frac{\Delta p}{p_0} \quad (2.11)$$

D_x is called **dispersion function** and satisfies:

$$D'' + k_s(s)D = \frac{1}{\rho} \quad (2.12)$$

The dispersion function depends on the lattice and like the lattice itself is periodical: $D(s+C) = D(s)$, with C the length of the ring.

The homogeneous equation is called Hill's equation:

$$x'' + k_s(s)x = 0 \quad (2.13)$$

Its solution describes the **betatron oscillations** around the design orbit. The betatron oscillations are the transverse oscillation of the particles in a circular accelerator around the equilibrium orbit. The solution of Eq. 2.13 is:

$$x_{Hom} = \sqrt{\varepsilon} \sqrt{\beta(s)} \cos(\varphi(s) - \varphi_0) \quad (2.14)$$

With ε, φ_0 integration constants and the β is the **betatron function** and depends on the lattice, thus is also periodical: $\beta(s+C) = \beta(s)$.

φ is the **phase advance** related with β :

$$\varphi(s) = \int_0^s \frac{ds}{\beta(s)} \quad (2.15)$$

The beta function and the dispersion function of ALBA's storage ring are shown in Fig.2.7.

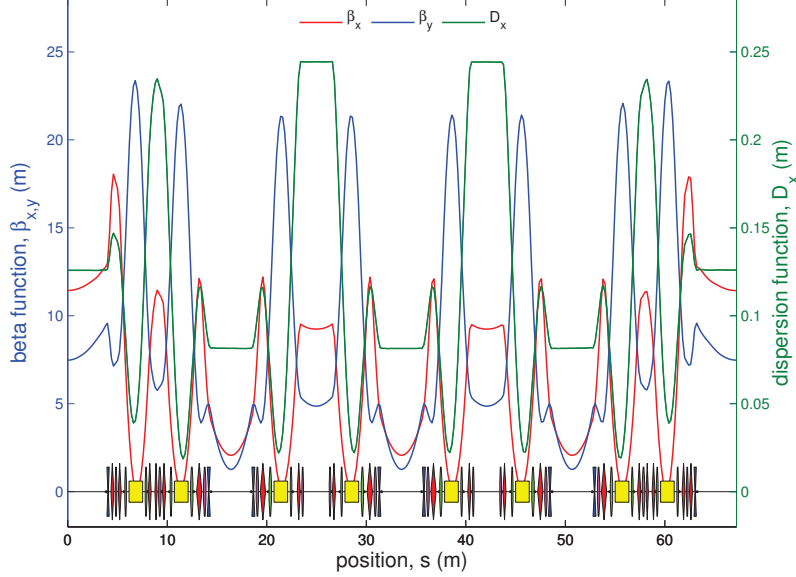


Figure 2.7: ALBA's storage ring's beta functions and dispersion function in one quarter of the machine

Related to the beta function the term **beta beating** is also used. It is defined by $\Delta\beta_{x,y}/\beta_{x,y}$ and it is useful because it gives an overview of the amount of imperfections in the ring. The less imperfections there are, the smaller the beta beating is. Therefore, after correcting the optics of the ring, the beta beating decreases.

Another important parameter to be defined is the **Betatron Tune**, which is the number of betatron oscillations per revolution:

$$Q_{x,y} = \frac{1}{2\pi} \oint \varphi(s) ds \quad (2.16)$$

2.4 ORBIT ERRORS

A small error in the magnetic field (ΔB) located at position s_0 along a length Δs produces an orbit deflection θ :

$$\theta = \frac{\Delta B \Delta s}{B \rho} \quad (2.17)$$

and the orbit displacement along the ring is described by [8]:

$$x(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2 \sin(\pi Q)} \cos(|\varphi(s) - \varphi(s_0) + \pi Q|) \quad (2.18)$$

Equation 2.18 is useful to define the so called orbit response matrix (ORM) explained in Section 2.6.

2.5 BEAM POSITION MONITORS

To measure the beam position in the ring, Beam Position Monitors (BPM) are used. It is a non-destructive diagnostics which uses the electromagnetic fields induced by the beam of electrons. Four metallic electrodes are situated crosswise at the vacuum chamber. As the beam passes through the chamber, a voltage is induced on the electrodes. The difference between the induced voltages is used to determine the position of the beam's centre of mass.

Figure 2.8 shows a representation of the displaced beam inside the vacuum chamber where A, B, C and D are the electrodes.

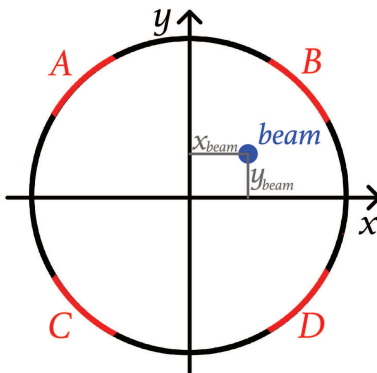


Figure 2.8: *Electron beam in vacuum tube and BPM electrodes (A,B,C,D)*

If the beam is centred, the signal at the electrodes will be the same. However, if the beam is displaced horizontally or vertically, the right and left or upper and down induced signal will be different. Using the "Delta over Sum" method the beam displacements can be obtained [9]:

$$x = \lambda_x \frac{(V_B + V_D) - (V_A + V_C)}{V_A + V_B + V_C + V_D} \quad (2.19)$$

$$y = \lambda_y \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D} \quad (2.20)$$

Where λ_x and λ_y are the sensitivity factors that depend on the specific geometry and material of the vacuum chamber.

2.6 ORBIT RESPONSE MATRIX

In ALBA's storage ring the orbit's horizontal and vertical position are measured at 120 BPMs distributed all along the circumference. As mentioned in Section 2.2, in order to correct the optics of the storage ring 88 horizontal corrector magnets (HCM) and 88 vertical corrector magnets (VCM) are used. Correcting the orbit implies that the HCM and VCM's strength makes the beam pass through the center of the BPMs. When a corrector magnet is switched on, the orbit is displaced following an equation like Eq. 2.18.

When acquiring the orbit response matrix (ORM) an horizontal change (Δx_{BPM}) is performed at all the BPMs positions as a result of a kick given by each one of the corrector magnets $\Delta\theta_{COR}$:

$$\Delta x_{BPM} = R\Delta\theta_{COR} \quad (2.21)$$

The elements of the ORM, R , are given by Eq. 2.18 [8]:

$$R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi Q} \cos (|\varphi_j - \varphi_i + \pi Q|) \quad (2.22)$$

Where i and j stand for the position where the orbit is observed (BPM) and the beam is kicked (Corrector). In ALBA the ORM has 120×88 elements for the horizontal plane and the same for the vertical plane.

The ORM contains information on the beam orbit's response to the dipole corrector magnets, HCM and VCM. As mentioned before, it is obtained by measuring the orbit deviations caused by an individual excitation (kick) of each corrector magnet. This matrix is generally used to correct the orbit at the BPM positions and is also useful to fit the optics of the lattice by obtaining the discrepancies between the design model and the real optics. In addition, since R_{ij} depends on the optical functions (β, φ, Q) it can be helpful to obtain information about the focusing errors in the lattice.

3 THE COMBINED FUNCTION DIPOLES IN ALBA

As mentioned in Section 2.2, the combined function dipoles are magnets that combine dipolar and quadrupolar fields. When two particles with the same energy but different horizontal positions pass through the combined function dipole, the integrated field the particles see is different. The magnets in ALBA's storage ring are defocusing in the horizontal plane, so that particles that have a positive horizontal displacement see less integrated field than the ones that have a negative horizontal displacement. Therefore, as illustrated in Fig. 3.1 particles with negative horizontal displacement (θ_3), in the direction to the centre of the ring, are deflected with more strength than the ones that have a positive horizontal displacement (θ_1).

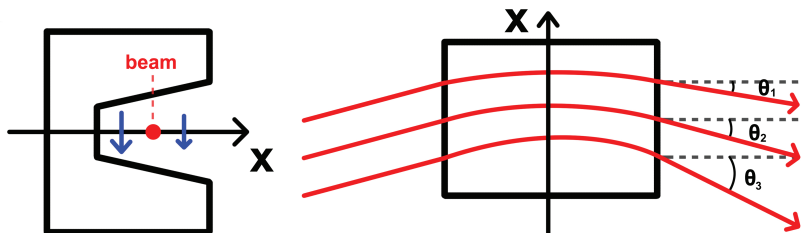


Figure 3.1: Combined function dipole magnet

In ALBA the 32 combined function dipoles are powered in series, which means that they have the same gradient value since they cannot be powered individually. Nevertheless, the dipole field can be varied individually by shifting the dipoles horizontally. Therefore, the integrated field that particles see when they pass through the combined function dipoles can be different from one to another. Moreover, as can be seen from Fig 3.1 if the gradient dipole is horizontally displaced in the positive direction the field that the particles see is lower.

In ALBA's storage ring, these magnets are equipped with a main dipole coil with 80 turns and a trim coil with 24 turns. These two different coils are powered separately. The 32 main coils are powered in series While the trim coils are powered individually and are unipolar with a range of 0-30 A, however, they are not currently used in the usual operation of the accelerator. The characteristics of each one of the 32 dipoles were measured with a Hall probe bench in the ALBA magnetic measurement laboratory before their installation. The main parameters are shown in Table 3.1 [10, 11].

Table 3.1: *Parameters of the combined dipoles magnets in ALBA based on the magnetic measurements. Where the maximum variation is the highest variation within the dipoles, Length is the gradient dipole’s magnetic length, k is the gradient’s normalised strength, G is the gradient’s strength and I is the power supply’s intensity.*

Parameter	Unit	Value	Maximum Variation
Length	m	1.374	±0.1%
Bending angle θ	rad	0.098	-
Bending radius	m	7.074	-
B (Field)	T	1.430	-
G (Field gradient)	T/m	-5.660	±0.4%
k (Normalised gradient strength)	m^{-2}	-0.567	±0.4%
I (main coil current)	A	519.091	-
Main coil turn number	-	80	-
Trim coils turn number	-	24	-

4 MATLAB MIDDLE LAYER, ACCELERATOR TOOLBOX AND LOCO CODE

MATLAB Middle Layer (MML) provides a MATLAB library of functions that can either communicate with the machine hardware or with Accelerator Toolbox for model-based applications. Therefore, it is used for routine machine operation, machine set-up and configuration control among others. When used to perform simulations, the Accelerator Toolbox is employed [12].

The Accelerator Toolbox (AT) is a library of functions to model storage rings and beam transfer lines [13]. It allows to create and manipulate accelerators’ lattice elements which are stored in MATLAB structures, and simulate tracking of the trajectories through them.

In ALBA, the storage ring is defined by a sequence of 1469 elements. Each element - dipoles, quadrupoles, sextupoles, BPMs, corrector magnets... - is defined by the physical parameters that define it, for example: length, magnetic field, particles’ energy, or also, the pass method, which is the function that calculates the trajectory of a particle going through the element. AT allows to track particles through the elements of the ring and to compute accelerators and beam parameters.

Learning MML and AT has been necessary in order to write the different scripts needed to perform the calculations. Another important code for this project is the LOCO code ([14],[15]).

LOCO is a code written in MATLAB used to find gradient errors (Δk) in the magnetic lattice of storage rings. Given a measured ORM, LOCO calculates the necessary changes in the gradient strengths to fit the model to the measured matrix.

Gradient strength’ changes are found by minimising the chi-squared difference between the model and the measured response matrices:

$$\chi^2 = \sum_{i,j} \frac{(R_{mod(i,j)} - R_{meas(i,j)})^2}{\sigma_i^2} \equiv \sum_{k=i,j} \vec{E}_k^2 \quad (4.1)$$

Where σ_i is the measured noise level of the i^{th} BPM. In ALBA the size of the ORM, as mentioned in Section 2.6, is 120×88 , therefore, it is a non-square matrix with 10.560 elements.

LOCO uses the Levenberg-Marquardt minimisation algorithm [14] that adjusts the model parameters to generate a vector, $\Delta \vec{E}$, that satisfies:

$$\vec{E}_k + \Delta \vec{E} = \vec{E}_k + \frac{\partial \vec{E}}{\partial k_l} \Delta k_l = 0 \quad (4.2)$$

Where k_l are the gradients varied to fit the ORM, which currently, in ALBA are the 112 quadrupoles [15], as mentioned in Section 1. Each column of the $\frac{\partial \vec{E}}{\partial k_l}$ matrix is the change in the ORM error vector with the fit parameter k_l .

$$\frac{\partial \vec{E}}{\partial k_l} \Delta k_l = -\vec{E} \quad (4.3)$$

Pseudo-inverting the matrix $\frac{\partial \vec{E}}{\partial k_l}$, the Δk_l that minimises the difference between the model and response matrix can be found. LOCO uses the Singular Value Decomposition method [14] to pseudo-invert the matrix and the Δk_l found can be used either to correct the current gradient strength calibration in the model or to apply the changes $-\Delta k$ in the real accelerator and approach the real optics to the model one.

5 ORM ANALYSIS AND GRADIENT ERROR FITTING

The purpose of this project is to identify the dipole's gradient errors by analysing the measured orbit response matrix of the ALBA lattice. To know how these errors varied along two years, about 50 ORMs acquired from September 2016 to November 2018 by the ALBA team have been analysed.

To analyse the ORM the LOCO code was used. In order to obtain the gradient error, the code uses the introduced measured ORM, as well as, the model lattice and the fitting parameters. So as to analyse the different data files for all dates, several scripts were written to perform the following operations:

- Find and load ORM files from appropriate folder and subfolders.
- Build the model lattice corresponding to the machine settings for each day.
- Analyse the ORM with LOCO and save the results (Δk) in its corresponding folder with a specific name and appropriate file type.
- Repeat for each day.
- Load each day's machine configuration and save Δk_{LOCO} in a MATLAB matrix (55x32) file. This file contains the Δk_{LOCO} for each 32 combined function dipole and each 55 dates.
- Plot Δk figures for each dipole, save them in the desired folder with the desired name.
- Save in different files information on the BPMs, the corrector magnets, the fit parameters and information about the response data, such as the configuration of the machine with its values, the lattice or the gradient errors.

6 INTERPRETATION OF THE RESULTS

The gradient errors (Δk) obtained using the LOCO code will be shown in this section.

Graphics have been plotted for each dipole in order to analyse the changes in the gradient error over time. These plots will be useful to assess the feasibility of correcting the gradient error. The main sources of these time-related errors are seasonal thermal changes or ground movements. An example of the gradient error in a dipole is shown in Fig. 6.1, the results for the other dipoles are included in Annex A.

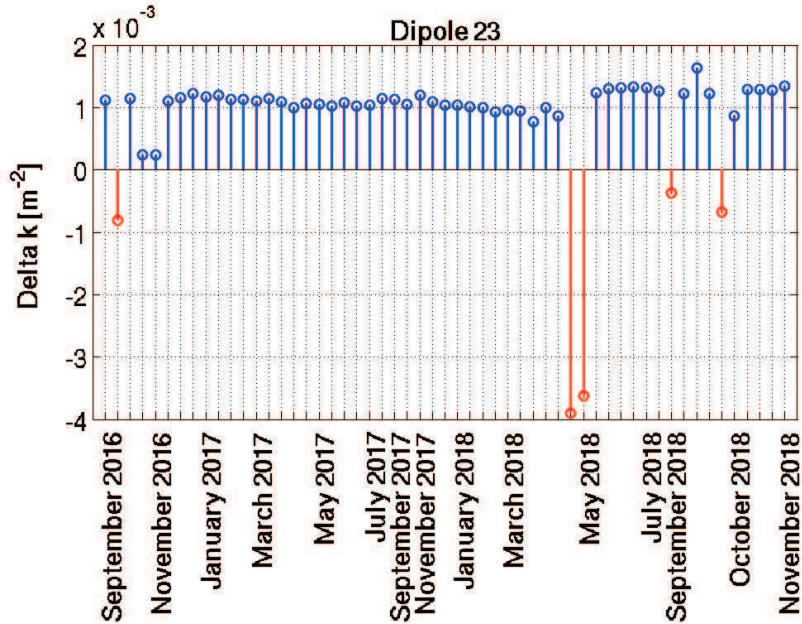


Figure 6.1: Δk for dipole 23: gradient error fitted by LOCO. The blue values of Δk is uniform along the 24 months studied and the red values are strange values attributed to wrong machine settings or BPM malfunctioning which were removed from further calculations.

After analysing and comparing all dipoles' graphics, some strange values marked in red in Fig. 6.1 were noticed. These values were removed from further calculation. The sudden changes in the Δk values observed can be attributed to wrong machine settings or to BPM malfunctioning when acquiring the ORM.

Figure 6.1 shows that for dipole 23 the average Δk is $1.13 \cdot 10^{-3} m^{-2}$ and the highest and minimum Δk are $1.64 \cdot 10^{-3} m^{-2}$ and $0.86 \cdot 10^{-3} m^{-2}$. It shows that the error Δk is very stable within the analysed period of 26 months. Also, it is shown that this magnet has a gradient error with respect to the nominal value ($-0.567 m^{-2}$ as reported in Table 3.1) of approximately 0.2%, which is within the the precision of the manufacturer specifications.

Other useful types of graphics that have been plotted are: one that describes the average Δk within all 32 dipoles for each measured ORM, Fig. 6.2, and another one that describes average Δk along with the magnetic measurements error for each dipole, Fig. 6.3.

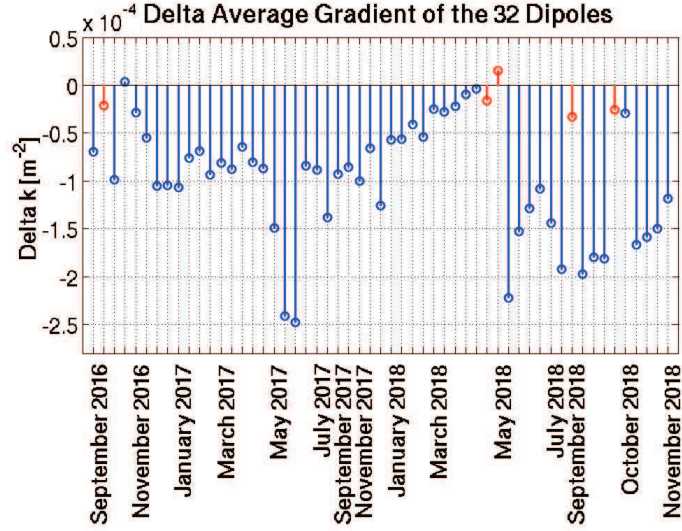


Figure 6.2: Δk averaged over all 32 dipoles plotted against the date along two years

Figure 6.2 shows the changes in the average gradient error within all 32 dipoles during the analysed period of time. Notice that the average Δk is below $2.5 \cdot 10^{-4} m^{-2}$, which is below 0.05% of the gradient strength $k = -0.567 m^{-2}$ reported in Table 3.1. Such results imply that there is a common small error in the 32 dipoles, which is a calibration systematic error resulting from the magnetic measurements.

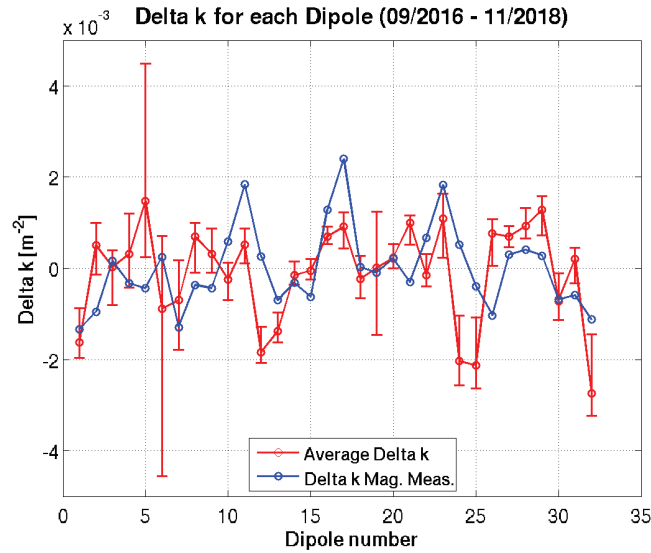


Figure 6.3: Average deviation Δk of each dipole along the two years (red circles). The error bars show the maximum and minimum variation in the set of measurements. The Δk from the magnetic measurements performed before the installation are plotted in blue.

Regarding Fig. 6.3, the average gradient error for each dipole is plotted along with the magnetic measurements error. Moreover, the maximum and minimum gradient error for each dipole are also plotted along with the average Δk . The Δk are of the same order of magnitude than the measurements precision, which was of the $\pm 0.5\%$.

The average Δk is considered to be the real combined function dipoles' calibration error. Its magnitude is useful to become acquainted with which have a higher calibration error. Concerning the minimum and maximum gradient error, dipoles 5, 6, 19, 24, 25 and 32 show large changes between the minimum and maximum values. This is due to controlled punctual changes in the orbit position performed by the ALBA team in the BPMs close to such dipoles. In all the other dipoles, the Δk vary within $\pm 0.5 \cdot 10^{-3} m$, which is $\pm 0.1\%$ of the nominal $k = -0.567 m^{-2}$ (Table 3.1), within the magnetic measurements precision.

Therefore, after having analysed all dipole errors, the correction of the calibration errors is considered feasible.

For further calculations and when simulating the changes shown in Fig 6.1 it has been taken into account that LOCO fits the dipoles' gradient so that the model lattice fits the measured ORM. However, since what is willing to achieve is correcting the actual gradient to set the design optics in the ring to make the gradients as similar as possible to the design values, a gradient change $-\Delta k$, opposite to the error detected by LOCO, has to be applied.

7 GRADIENT ERROR CORRECTION AND COMPENSATION OF THE DIPOLAR FIELD CHANGE

As mentioned in Section 6, the gradient change that has to be applied to the dipole magnets has the opposite sign than the one found by LOCO. In this section it will be explained the correction of the gradient error and the compensation of the change in the dipolar field to keep the orbit unchanged.

Since the 32 dipoles are all powered in series with a common power supply, as indicated in Section 2.2, the trim coils, which instead are powered individually, are used to vary each magnet strength independently. To change the gradient error by $-\Delta k$ the trim coils' current has to be varied. The calculation of ΔI_{TRIM} is straight-forward if the Δk is known by using the magnetic calibrations previously performed in the laboratory of magnetic measurements by the ALBA team. Such calibrations of field with excitation currents are:

$$\Delta G [T/m] = 2.16 \cdot 10^{-3} \Delta I_{TRIM} [A] \quad (7.1)$$

$$\Delta B [T] = 5.71 \cdot 10^{-4} \Delta I_{TRIM} [A] \quad (7.2)$$

Then, ΔI_{TRIM} to correct the gradient errors are:

$$\Delta G = \frac{\Delta k}{B\rho} \quad \rightarrow \quad \Delta I_{TRIM} = \frac{\Delta G}{2.6 \cdot 10^{-3}} = \frac{\Delta k \Delta G}{2.6 \cdot 10^{-3} B\rho} \quad (7.3)$$

The dipoles have $k < 0$ and the electrical connections are such that if $\Delta I_{TRIM} > 0$, $\Delta k < 0$.

To calculate ΔI_{TRIM} a MATLAB script has been developed that performs the following operations:

- Load the file that contains the Δk values.
- Load the initial configuration of the storage ring's elements of the last data acquired.

- Compute and obtain the initial values necessary for further calculation: beam energy, rigidity, dipole length, B_0 , θ_0 ...
- Compute $\Delta k_{average}$ for each combined function dipole.
- Calculate ΔI_{TRIM} using Eq. 7.3
- Save the ΔI_{TRIM} values in a text file and a MATLAB file.
- Plot the ΔI_{TRIM} with respect to each combined function dipole.

The ΔI_{TRIM} values to correct the errors depicted in Fig. 6.3 are shown in Fig. 7.1.

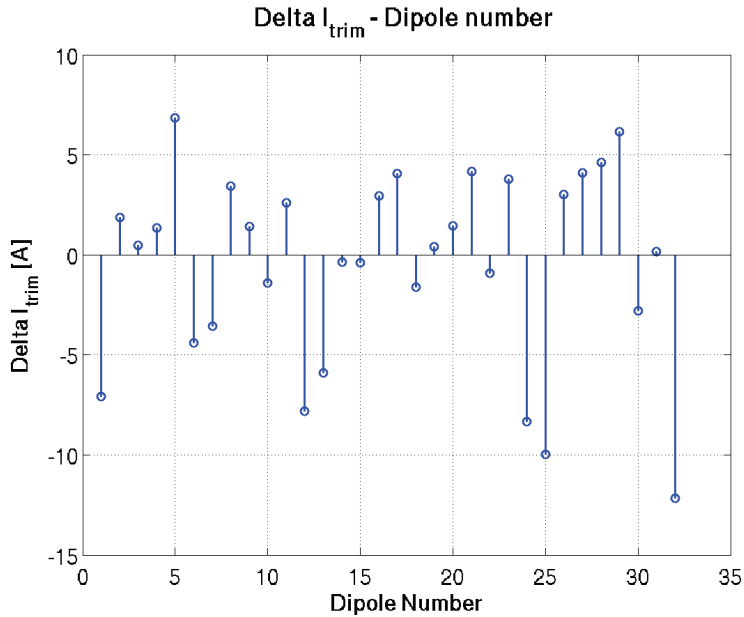


Figure 7.1: ΔI_{TRIM} to correct the gradient error ΔK obtained by LOCO and shown in Fig. 6.3

As mentioned in Section 2.2, before 2018, the trim coils were not powered yet and the magnetic field was generated only by the power supply of the main coils. In 2018, unipolar power supplies were connected to the trim coils with a current range from zero to +30 A. However, the ΔI_{TRIM} obtained (Fig. 7.1) are both positive and negative.

To allow bipolar changed and keep the beam energy unchanged, trim coils can be all switched on and set at +15 A and the main dipole power supply has to be decreased by 4.5 A. For this reason, no ΔI_{TRIM} larger than ± 15 A can be applied. As shown in Fig. 7.1, the ΔI_{TRIM} with value closest to ± 15 A, dipole 32, is $\Delta I_{TRIM} = -12.5$ A. Also, taking into account that the range of the trim coils' power supply is from 0 to 30 A, the highest positive value of ΔI_{TRIM} to be applied is in the combined function dipole 5, which leads to a final I_{TRIM} value of +21.8 A, which is well below the limit value.

Up to this point, we would have corrected the combined function dipoles' gradient errors, however, the dipolar field would also change (see Eq. 7.2) which is not desirable, as the deflection angle would change. This would lead to both, a change in the orbit, and a change in the beam energy.

In order to correct the unwanted dipolar field change, two strategies can be employed: The first one is using the horizontal corrector magnets (HCM) close to each dipole to give an extra kick in the appropriate horizontal direction. This would compensate the field's change seen by the beam when going through the combined function dipole. The second strategy is shifting horizontally the dipole to change the integrated dipolar field that sees the beam when going through it. This, however, is more laborious and almost irreversible. Both possibilities have been studied and discussed for each combined function dipole in Sections 7.1 and 7.2.

7.1 COMPENSATION OF THE DIPOLAR FIELD CHANGE WITH HORIZONTAL CORRECTOR MAGNETS

One of the techniques that can be used to correct the orbit distortion caused when applying the ΔI_{TRIM} to the trim coils is using the HCM. What we are willing to achieve is to keep the same horizontal orbit throughout the ring. The vertical position has not changed because the kick given by the trim coil variation is in the horizontal plane.

A simulation was performed with Accelerator Toolbox (AT) using a measured ORM, R, and the simulated orbit positions x_{BPM} at the BPMs after applying the ΔI_{TRIM} . The HCM's kicks ($\Delta\theta_{HCM}$) needed to correct to zero the orbit in the BPMs were calculated by solving the Eq. 7.4.

$$x_{BPM} + R\Delta\theta_{HCM} = 0 \quad (7.4)$$

Pseudo-inverting the R matrix with an SVD we obtain the desired $\Delta\theta_{HCM}$:

$$\Delta\theta_{HCM} = -R^{-1}x_{BPM} \quad (7.5)$$

A dedicate script has been developed to simulate and plot the results. This functions perform the following operations:

- Load the Δk values and the initial configuration of the elements in the storage ring.
- Define the elements of ALBA's storage ring using Accelerator Toolbox.
- Compute and obtains initial configuration values useful for further calculation
- Load the ORM, R, for each date.
- Simulate with AT the Δk changes at the BPMs, introducing the ΔI_{TRIM} kicks in the trim coils.
- Obtain the horizontal beam position after having simulated the kicks.
- Calculate the inverse matrix, R^{-1} , with the Singular Value Decomposition method (SVD) [14].
- Calculate the $\Delta\theta_{HCM}$ desired using Eq. 7.5.
- Save the data computed (ΔI_{HCM}) in a text file and a MATLAB file.
- Plot ΔI_{HCM} for each dipole. Therefore, 32 different graphs are plotted.
- Selects the highest ΔI_{HCM} contribution for each dipole and plots them.
- Plots the initial I_{HCM} settings and the configuration after adding the ΔI_{HCM}

The results obtained as explained before, are calculated individually for each dipole gradient change. Two typical cases are shown in Fig. 7.2, all the others can be found in annex B.

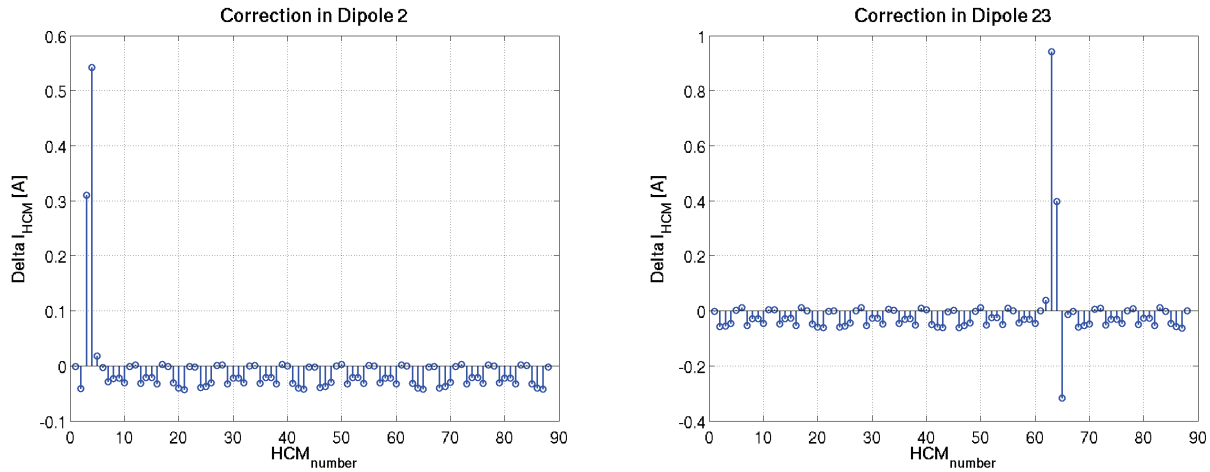


Figure 7.2: *Simulated Horizontal Corrector Magnets' ΔI for dipoles 2 and 23 to compensate the field changes when applying the needed trim coils' ΔI as shown in Fig. 7.1*

Figure 7.2 shows the HCM's intensity changes needed in order to compensate the change in the field produced when applying ΔI_{TRIM} in a single dipole. As it can be seen, the highest contribution of these changes are in the two or three corrector magnets near the corrected dipole. The rest of the HCMs contain a very small contribution which is considered negligible.

Figure 7.3 shows the changes in the HCMs if the ΔI_{TRIM} were applied to all the dipoles together with the highest contribution of each HCM.

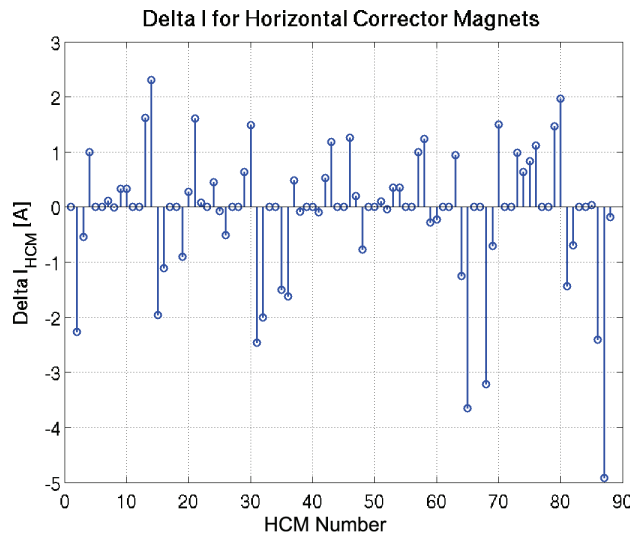


Figure 7.3: *Simulated largest ΔI_{HCM} contribution to be applied when all the 32 dipole ΔI_{TRIM} are applied*

In Fig. 7.3 it is plotted the highest HCM contribution for each dipole calculated individually. By doing it in this manner, each dipole can be studied individually and the two strategies for compensating the unwanted dipolar field change can be considered independently for each dipole.

Figure 7.4 shows the result of adding the ΔI_{HCM} to the I_{HCM} settings already used in the current storage ring operation.

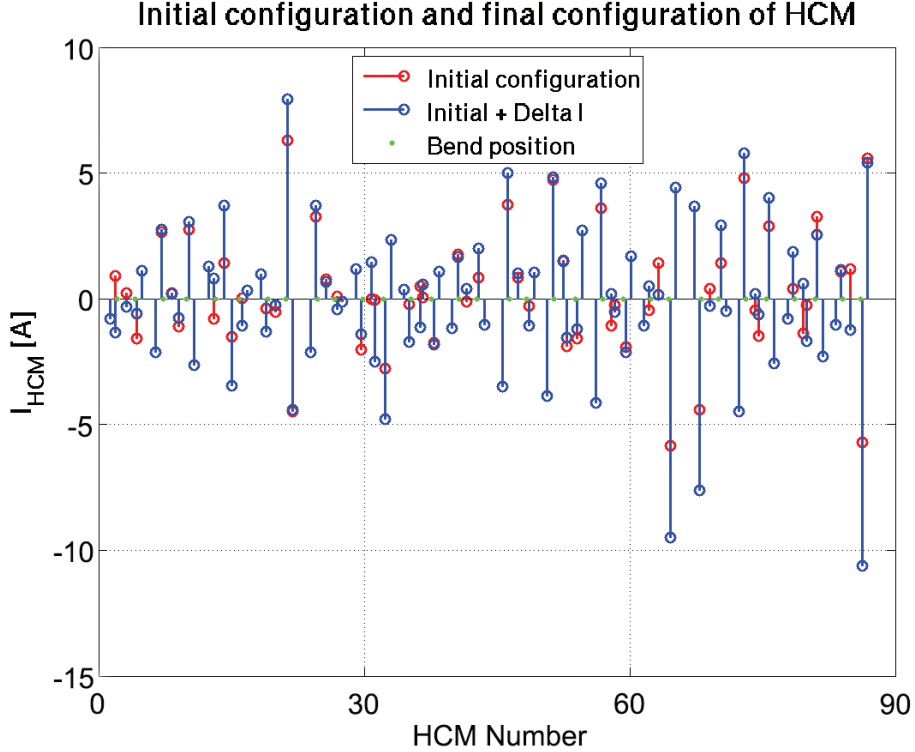


Figure 7.4: Simulated initial (red) and final (blue) settings after applying ΔI_{HCM}

As shown in Fig. 7.4, in most of the cases, the final configuration value is larger in absolute value or nearly the same than at the initial configuration. The cases with the highest final configuration values will have to be studied in detail since the intensity limit of the HCMs power supplies is ± 10 Amperes. There are at least four cases corresponding to HCM near dipoles 8, 24, 25 and 32 where the HCM's intensity would be close to the limit, ± 10 A, and further studies have to be done.

7.2 FIELD CHANGES COMPENSATION BY SHIFTING THE DIPOLES

The second option that can be used to compensate the field change is taking advantage that the dipoles are actually combined function dipoles. Therefore, as explained in Section 2.2, if the dipole is shifted in the horizontal plane, hence in the radial direction, the intensity of the field seen by the beam changes while the gradient does not. If displaced in the direction of the centre of the ring, the integrated field seen by the particles is higher. The technical precision of shifting a magnet is about $100 \mu\text{m}$ and applying the displacements with accuracy is laborious, time-consuming and almost irreversible.

Once the ΔI_{TRIM} is known, calibration of the dipole trim coils provided by the ALBA team (Eq. 7.2) are used. The relation between Δx_{Dipole} and ΔB is:

$$\Delta x_{Dipole} = \frac{\Delta B}{G_0} \quad (7.6)$$

with G_0 initial field gradient in Table 3.1.

To compute the values of Δx_{Dipole} a MATLAB function that performs the following operation has been developed:

- Load the initial configuration and the values of ΔI_{TRIM} .
- Compute and obtains initial configuration values necessary for following calculation.
- Use Eq. 7.6 to compute the shifts Δx_{Dipole} .
- Save the results obtained in a text file and in a MATLAB matrix file.
- Plot Δx for each combined function dipole.

The Δx_{Dipole} obtained are the ones shown in Fig. 7.5.

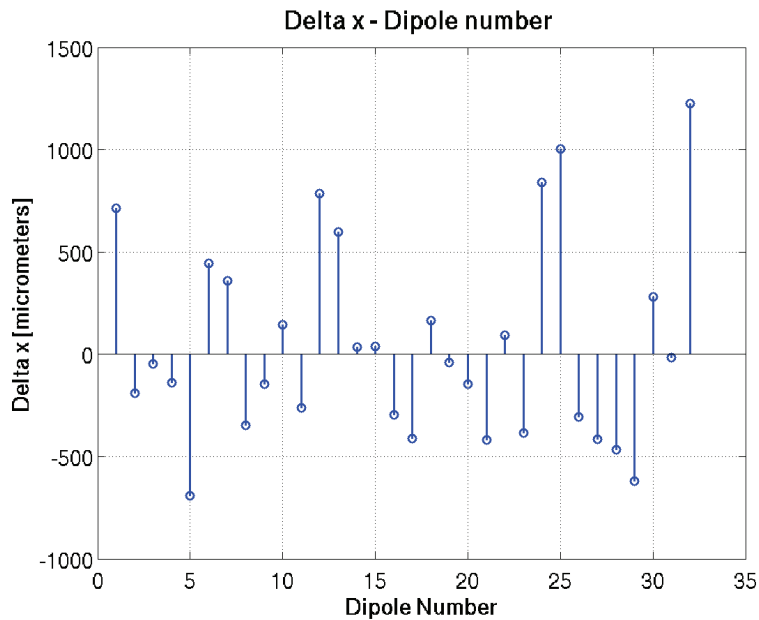


Figure 7.5: Calculated displacements Δx to apply to the dipoles in order to compensate the change in the dipolar field produced by the trim coils.

As shown in Fig. 7.5 the necessary dipole's shifts vary from nearly zero to over $1mm$. Only displacements up to $1mm$ are physically and technically possible. Moreover, since the technical precision of the displacements is about $100 \mu m$, displacements lower than $300 \mu m$ are not considered useful.

Dipoles 24, 25 and 32 shifting values are too high to be applied and other solutions will have to be considered. Furthermore, dipoles 2, 3, 4, 9, 10, 14, 15, 18, 19, 20, 22 and 31 shifting values are too low to be considered feasible to be applied, so only the compensation with HCM has to be considered.

8 FIRST TEST OF BEAM OPTICS CORRECTION WITH THE DIPOLE TRIM COILS

In this Section it will be explained the first test performed by the ALBA team for beam optics correction with the dipoles trim coils on the 17th of February 2019.

As mentioned in Section 2.2, the dipoles' trim coils in ALBA were switched off. Since they have an unipolar power supply with a range from 0 to 30 A and the ΔI_{TRIM} that has to be applied is positive and negative, the trim coils were set at +15 A. However, the integrated magnetic field that particles see when going through the dipoles has to be kept unchanged. Taking this into account and that the number of trim coils is 24 and the number of main coils is 80, as mentioned in Table 3.1, if the trim coils are set at +15 A the main coils' power supply current has to be decreased by 4.5 A.

Firstly, the dipole's power supply current was decreased from 519.09 A to 514.48 A and set the trim coils' at +15 A making sure all the storage ring parameters were kept unchanged, in particular, the dipoles' current was finely adjusted to reproduce the same betatron tunes as the initial ones.

An ORM with quadrupoles settings at the design values was measured and the beta beating – explained in Section 2.3 – reconstructed with LOCO was of the $\pm 10\%$ in the horizontal plane and $\pm 20\%$ in the vertical plane, as shown in Fig 8.1.

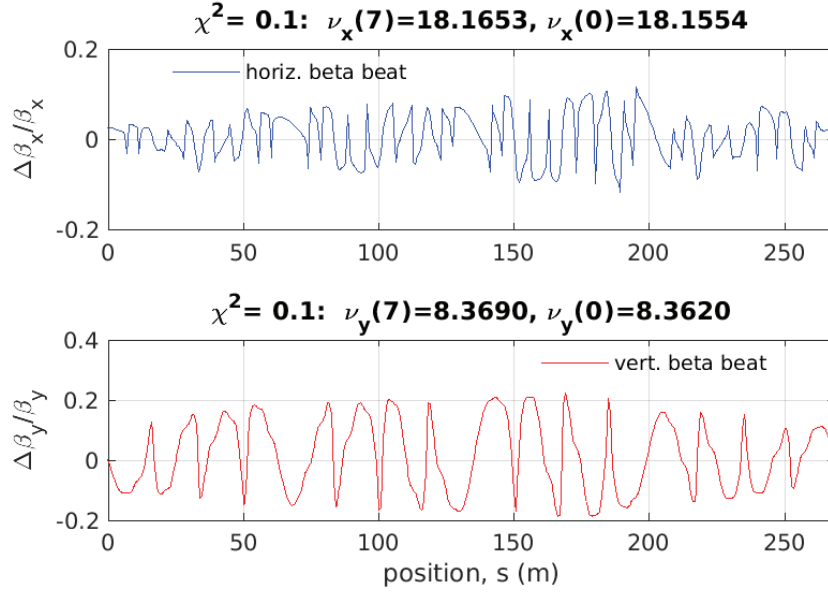


Figure 8.1: Beta beat obtained before the changes in the trim coils' current.

The trim coils' current changes obtained with LOCO and the HCM current change to be applied in order to correct the orbit are shown in Fig 8.2. The results obtained were as expected from the previous studies in Sections 6 and 7, however, they show that the maximum trim coils changes is over -15 A in dipole 32 and the 65th and 87th I_{HCM} would have a value over the limit of -10 A. Such values are too large and if they were applied they would pass the power supply limit. For such reason, only the 60% of the changes shown in Fig 8.2 were applied.

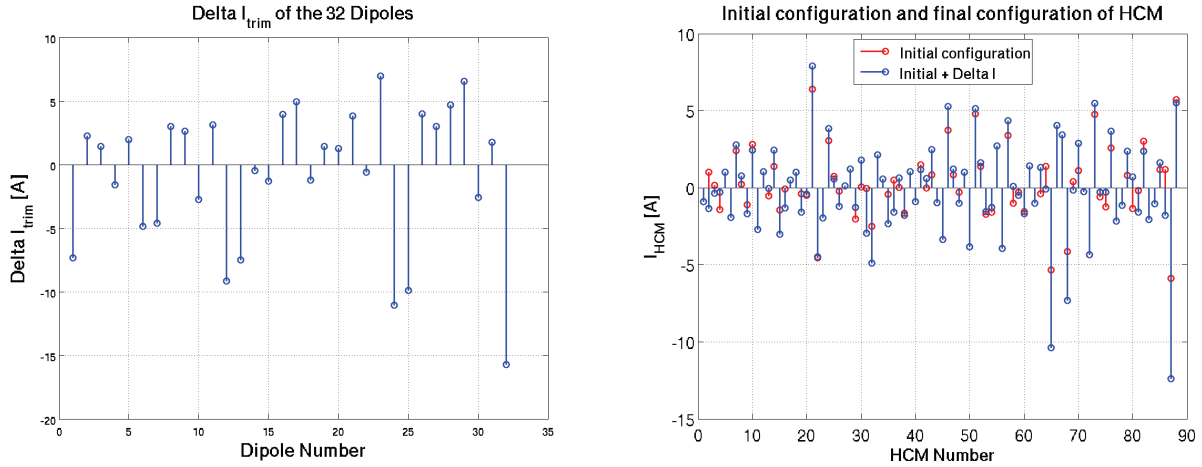


Figure 8.2: **Left:** Trim coil's current change obtained using the LOCO code. **Right:** HCM's current change

The beta beating, after applying the 60% of the changes is shown in Fig 8.3, was reduced from 10% in the horizontal plane and 20% in the vertical plane to 5% in both horizontal and vertical plane.

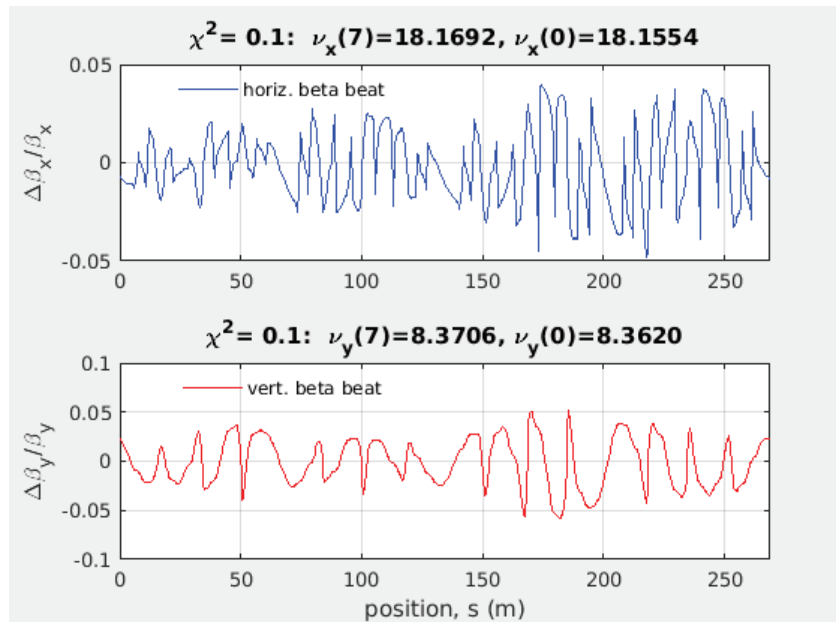


Figure 8.3: Beta beat obtained after the 60% of the changes in the trim coils' current were applied.

Therefore, correcting the combined function dipoles' gradient error has lead to a decrease in the beta beating. LOCO was performed again, however, in the 32nd dipole, the intensity change in the 87th was of $-4A$ and this HCM was already set at $-9.3A$ so no further correction was possible.

9 CONCLUSIONS

The Orbit Response Matrices (ORM) obtained by the ALBA team during 26 months were analysed in order to observe changes in the combined function dipole's gradient error and consider the feasibility of further optics correction. Figure 6.1 and figures shown in Annex A show stable gradient errors within the precision of the magnetic measurements. Some ORM had strange values that were removed from further calculations and were attributed to wrong machine settings or Beam Position Monitors malfunctions when acquiring the ORM. Since the gradient errors are considered negligible during a long period of time, the optics corrections is considered feasible.

The changes in the combined function dipoles' gradient were obtained using the LOCO code and a set of MATLAB scripts were written to perform the calculations. Each combined function dipole is equipped with a main coil and a trim coil. The 32 main coils are powered in series and the trim coils are powered individually for each dipole with a range from 0 to 30 A. Therefore, the trim coils were used to change the gradient strength in each dipole for its optics correction. To do so, the average gradient error during the studied period of time for each dipole was calculated and the changes in the trim coils' intensity to correct the gradient error (Δk) are shown in Fig. 7.1. The trim coils current changes (ΔI_{TRIM}) show both positive and negative changes no larger than 13 A.

Correcting the combined function dipoles' gradient error changes the integrated field particles see when going through the dipole, which produces a change in the beam orbit. There are two strategies that can be used to correct this unwanted dipolar field change; using horizontal corrector magnets (HCM) or taking advantage that the ALBA dipoles are, in fact, combined function dipoles and shifting them in the radial direction creates a change in the dipolar field, as explained in Section 2.2.

The results for the field compensation using the HCM are shown in Section 7.1. The initial HCM's configuration is plotted along with the final configuration (useful operation configuration + ΔI_{HCM}) in Fig 7.3. In most of the cases, the final HCM intensity value is larger than the initial one. There are some cases, HCM near dipoles 8, 24, 25 and 32 where the final value is too close to the limit of the HCM power supply and other measures to decrease the initial settings need to be taken before applying the trim coil's changes.

The second strategy is compensating the field change by shifting the combined function dipoles horizontally. Plotted in Fig. 7.5 is the Δx_{Dipole} calculated. Such values vary from nearly zero to over 1 mm. As mentioned in Section 7.2, only displacements in the rage of 300 to 1000 μm are possible. Therefore, for displacements that are below this range only HCM correction can be used (dipoles 2, 3, 4, 9, 10, 14, 15, 18, 19, 20, 22 and 31) while for dipoles above the this range (dipoles 25 and 32) other techniques must be considered.

Since shifting the dipoles is a laborious technique, compensating the field with HCM is more convenient to be considered. However, for dipoles 8, 24, 25 and 32 realignment should be considered or a combination of both strategies should be studied.

The first test of beam optics correction using the combined function dipoles' trim coils and compensating the field only using the HCM was as expected from the results obtained. Dipole 32 showed the largest trim coil intensity change and some HCMs were near or over the limit, therefore, only the 60% of the changes were applied. Nevertheless, by applying these changes the beta beating was reduced from $\pm 10\%$ in the horizontal plane and $\pm 20\%$ in the vertical plane to $\pm 5\%$ in both planes, as shown in Section 8. To be able to apply the 100% of the trim coil current changes the large HCM values close to dipole 32 must be decreased by realigning the magnets close to them.

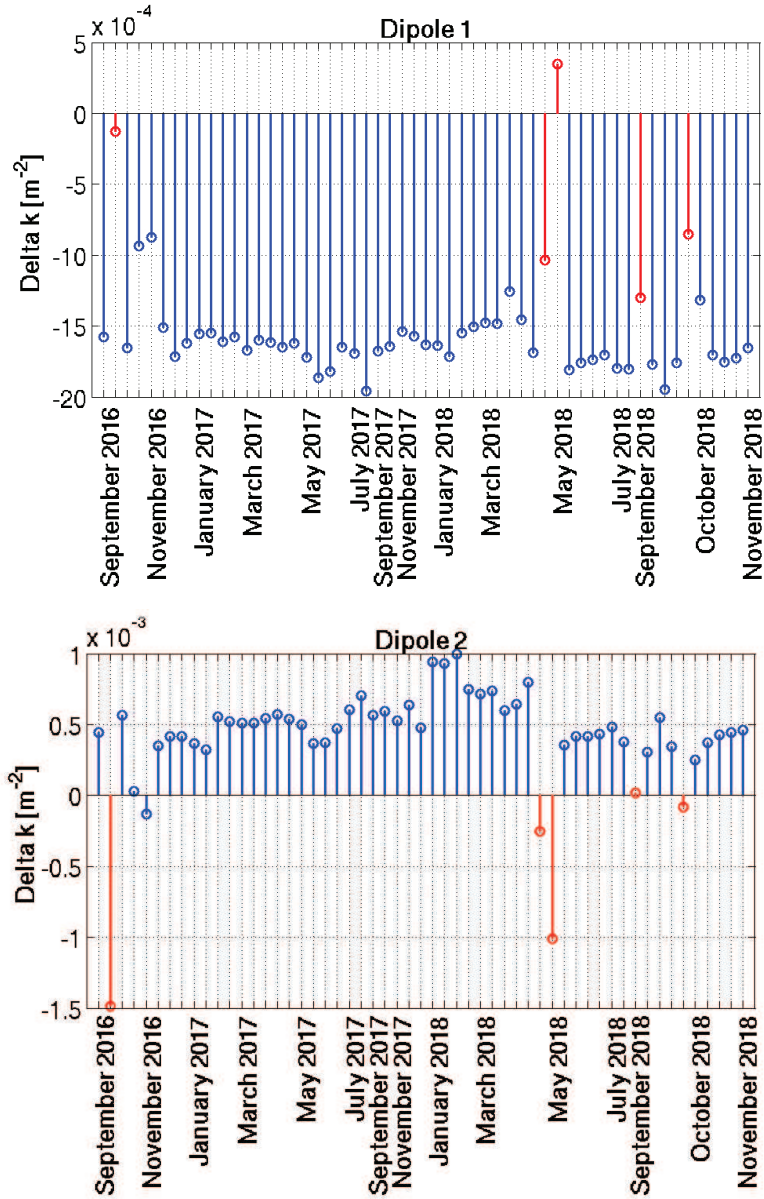
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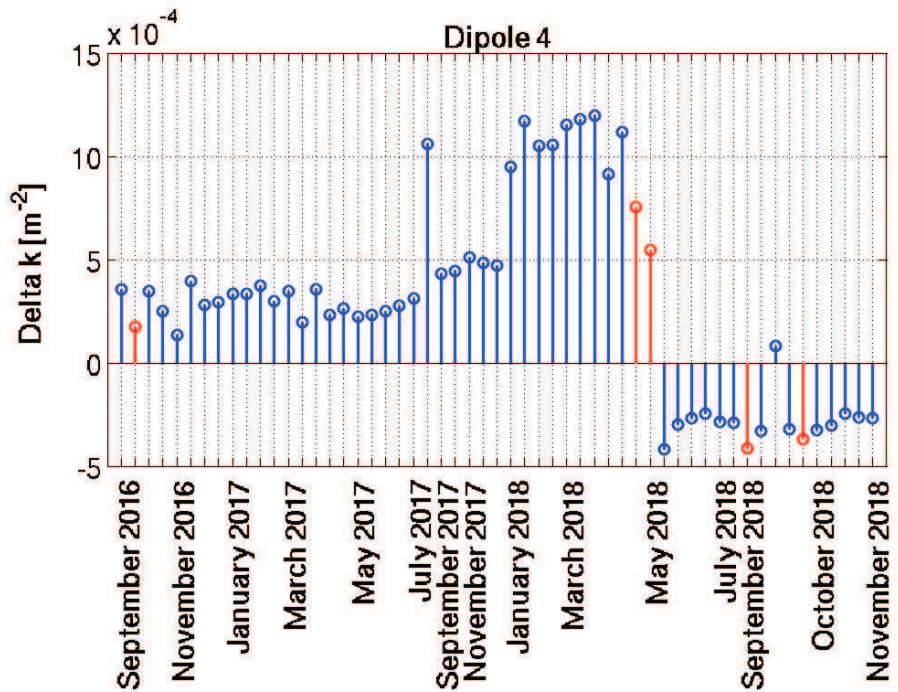
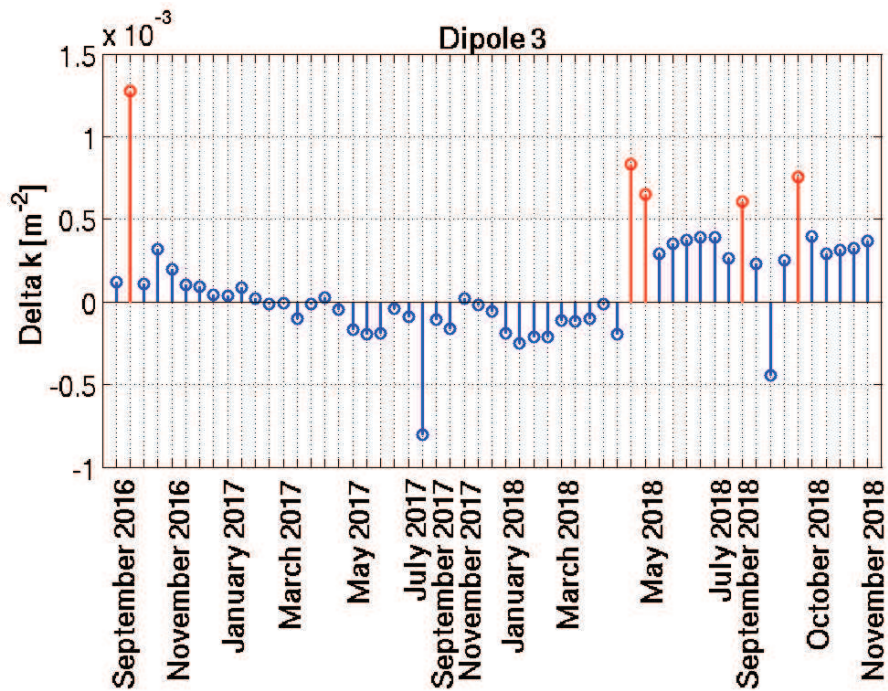
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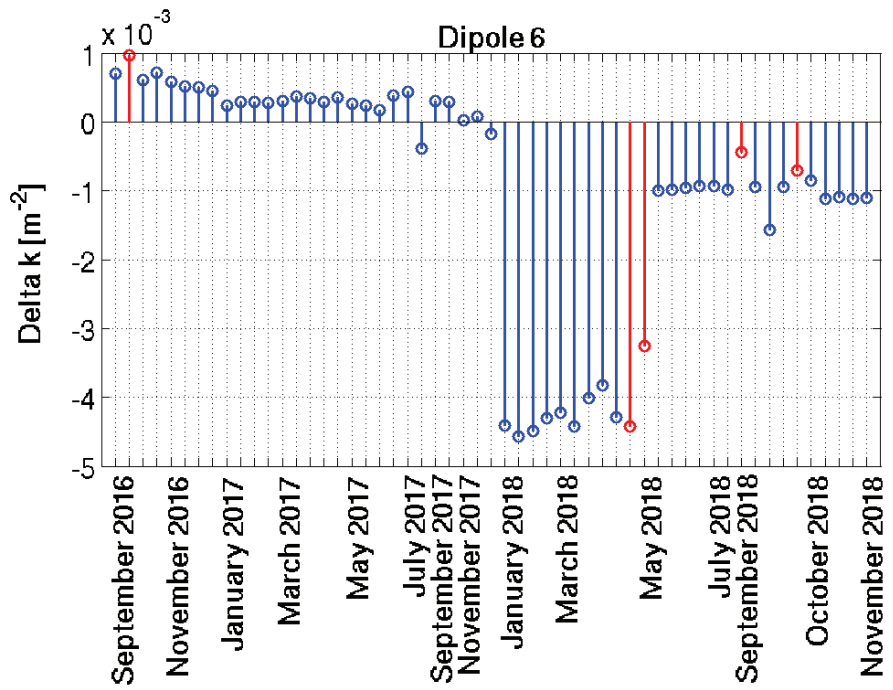
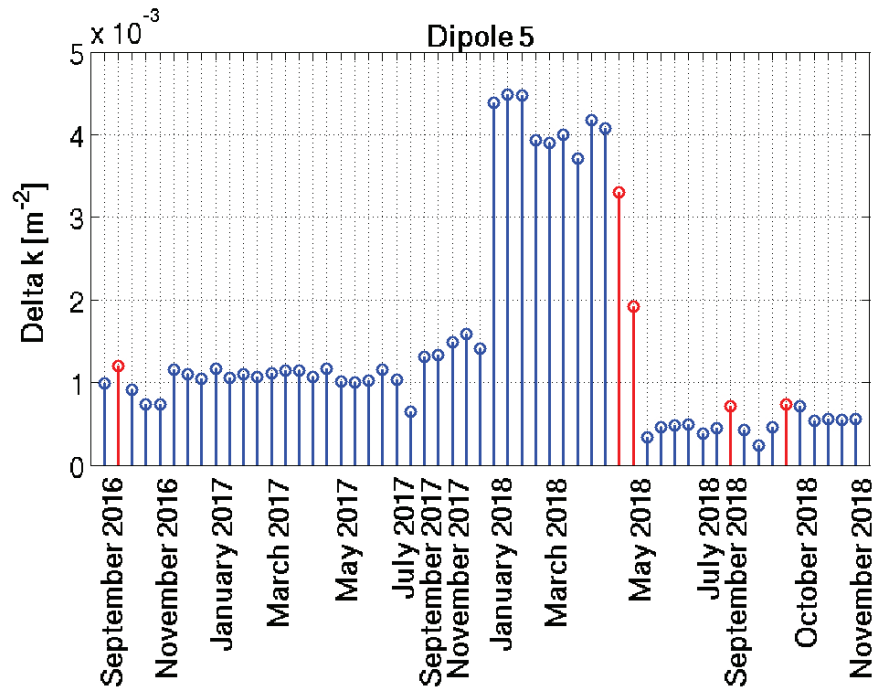
ANNEXES

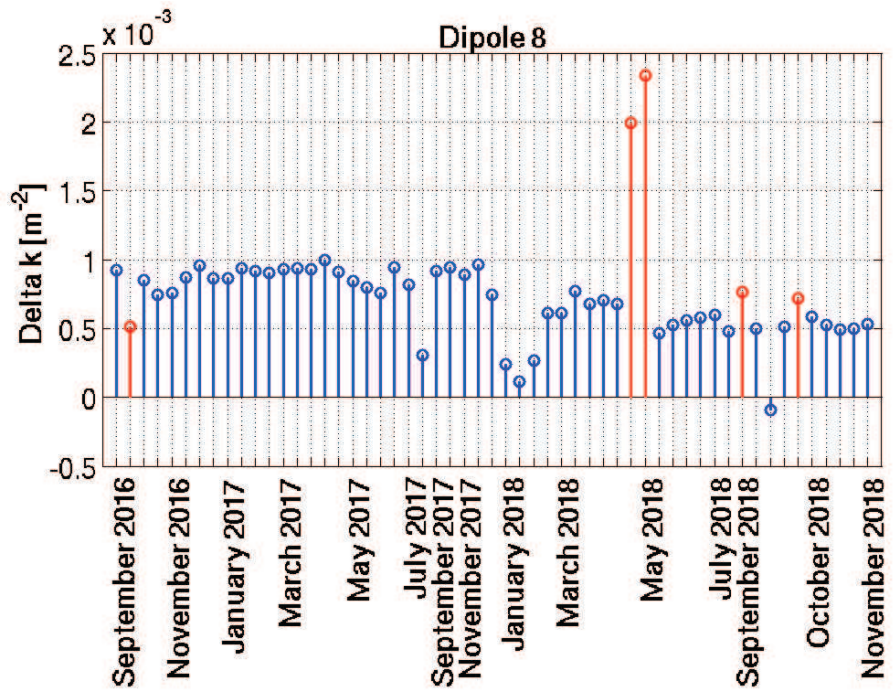
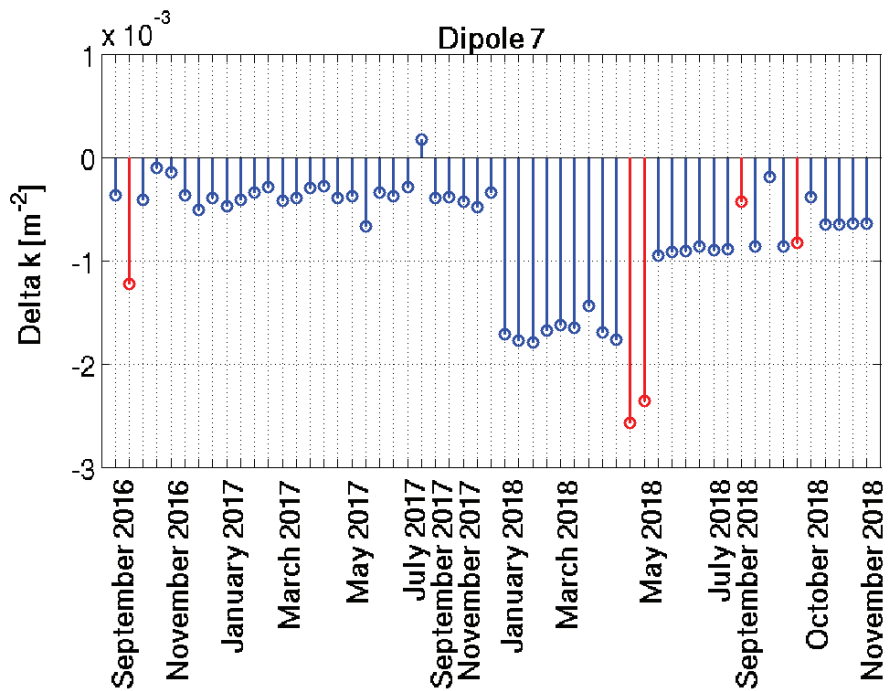
A COMBINED FUNCTION DIPOLES' GRADIENT ERROR

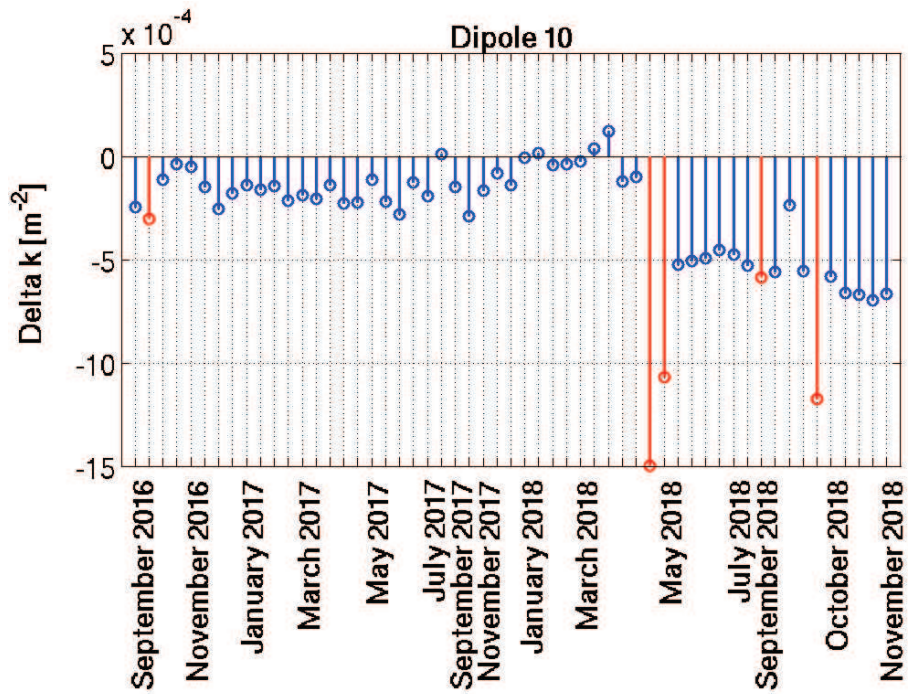
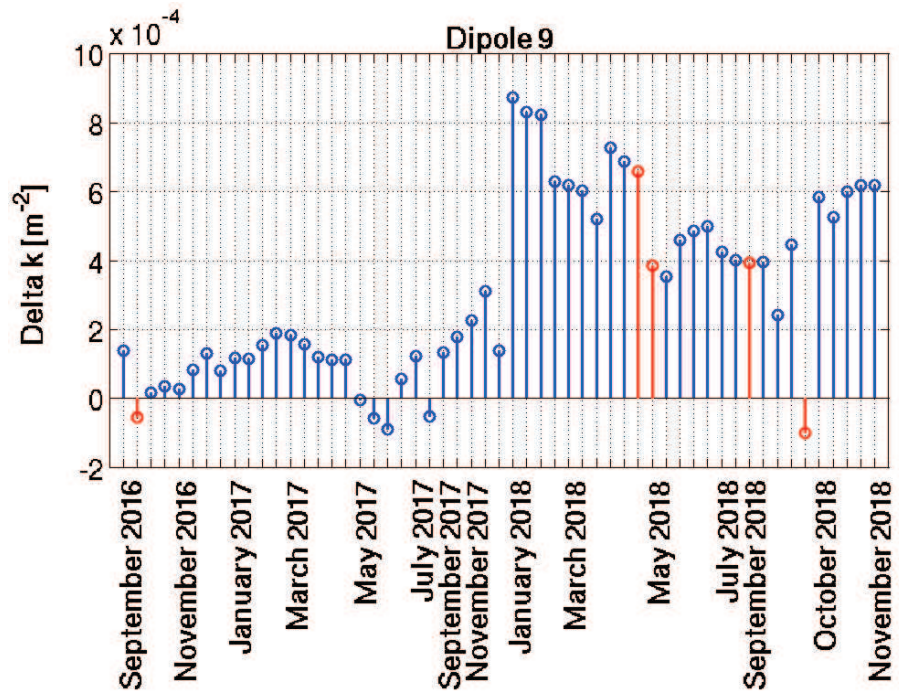
In this section the plots for all the 32 combined function dipoles' gradient error are shown. Red values are considered wrong values due to error in acquiring the ORM or BPM malfunctions and were eliminated from further calculations.

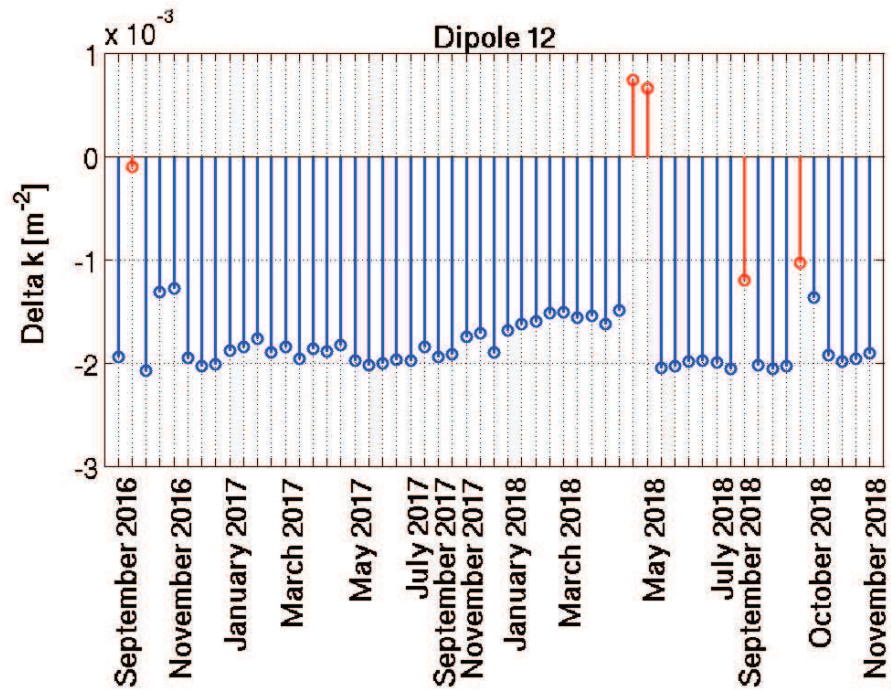
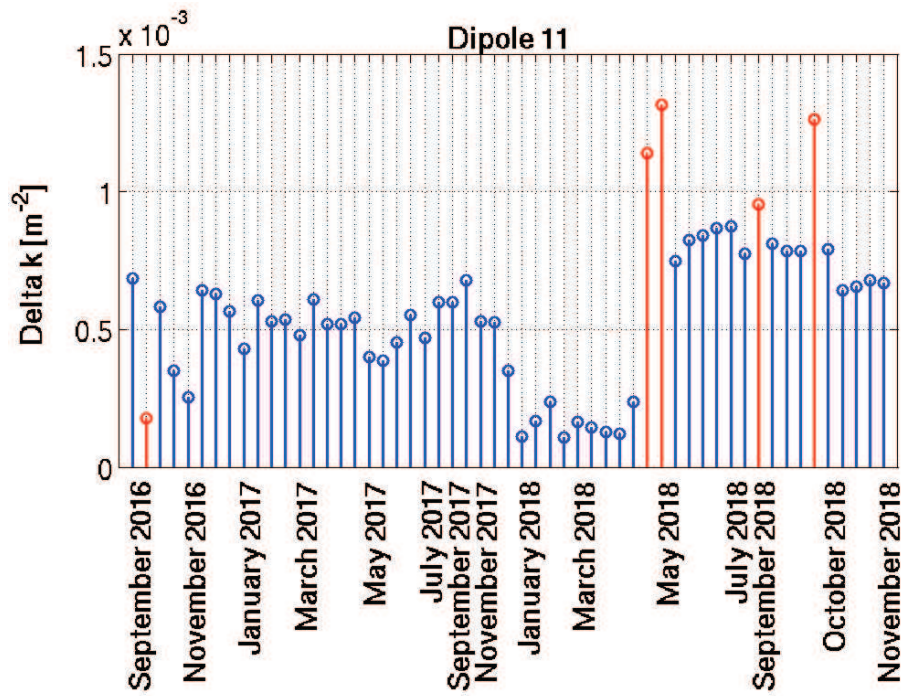


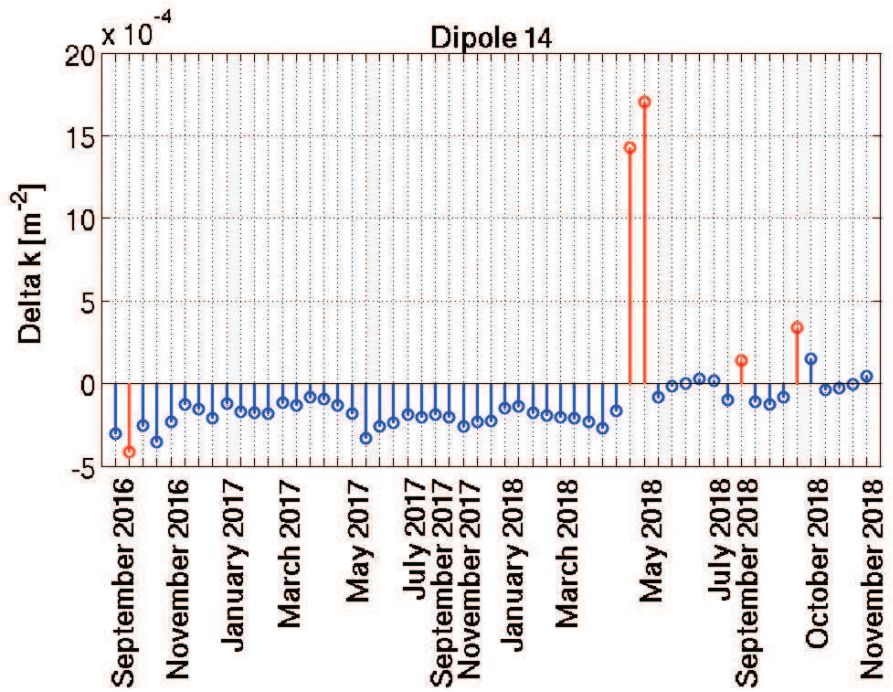
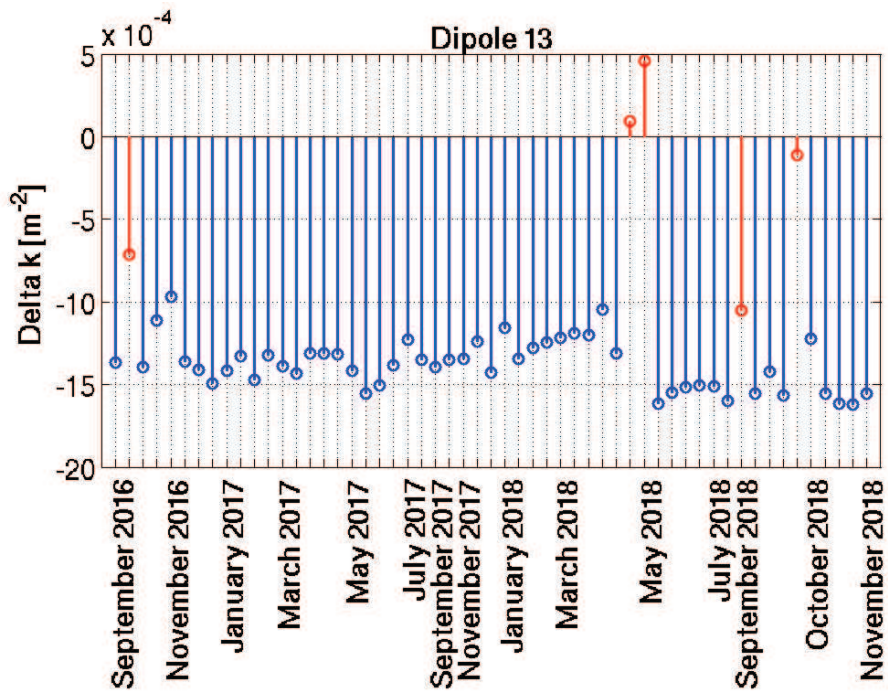


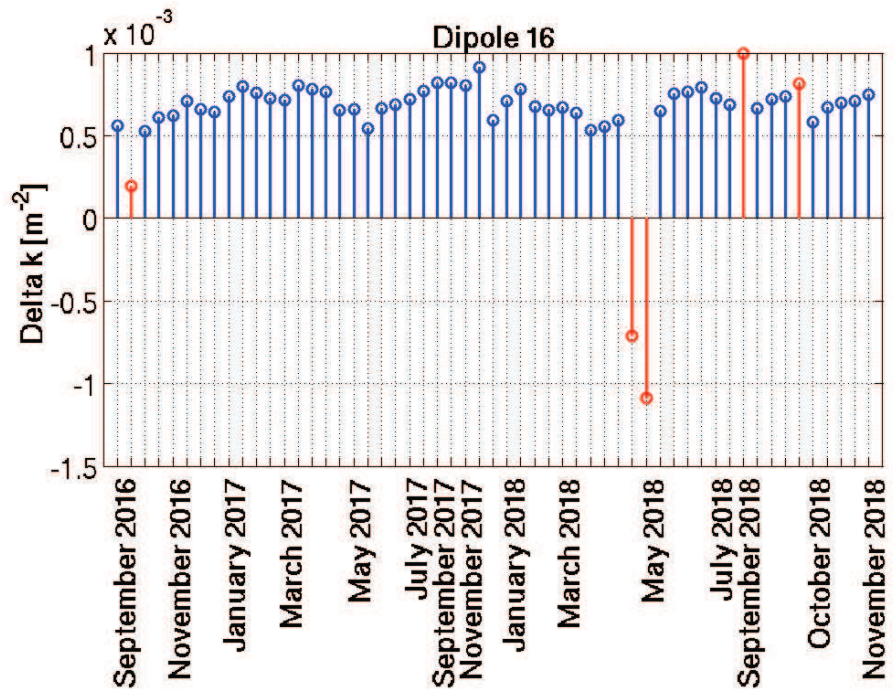
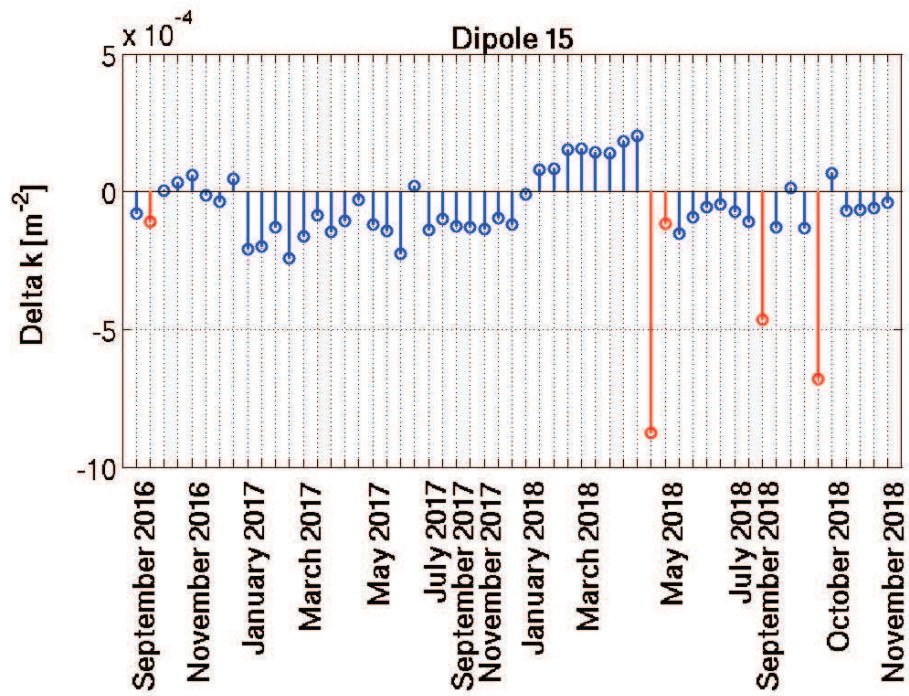


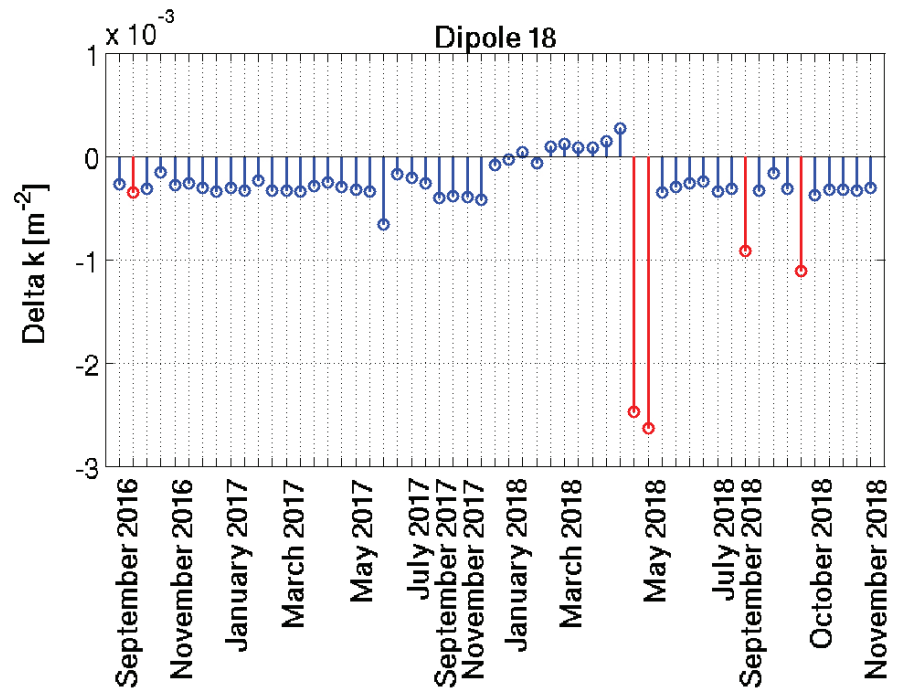
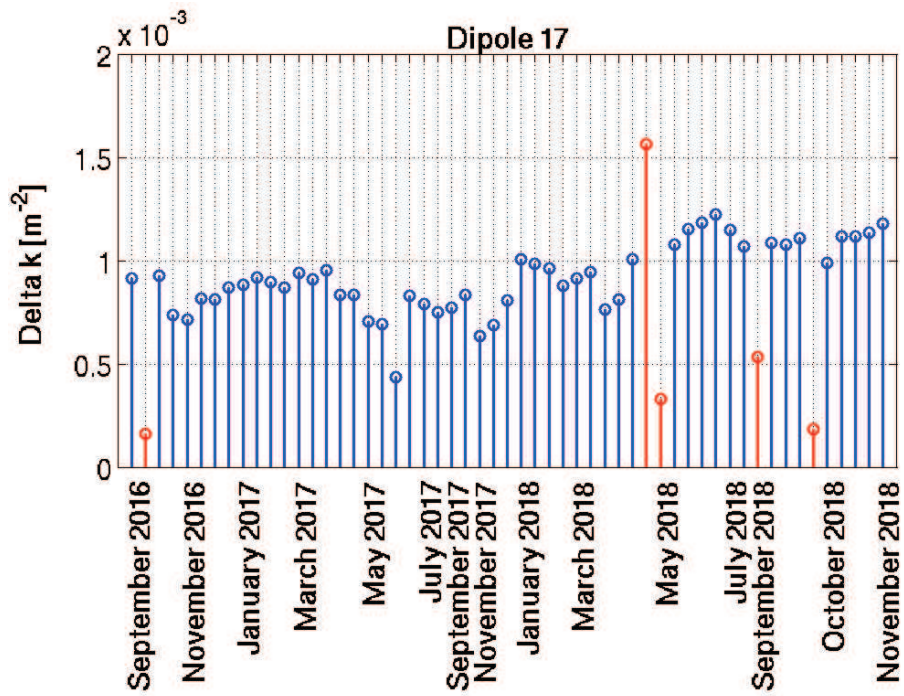


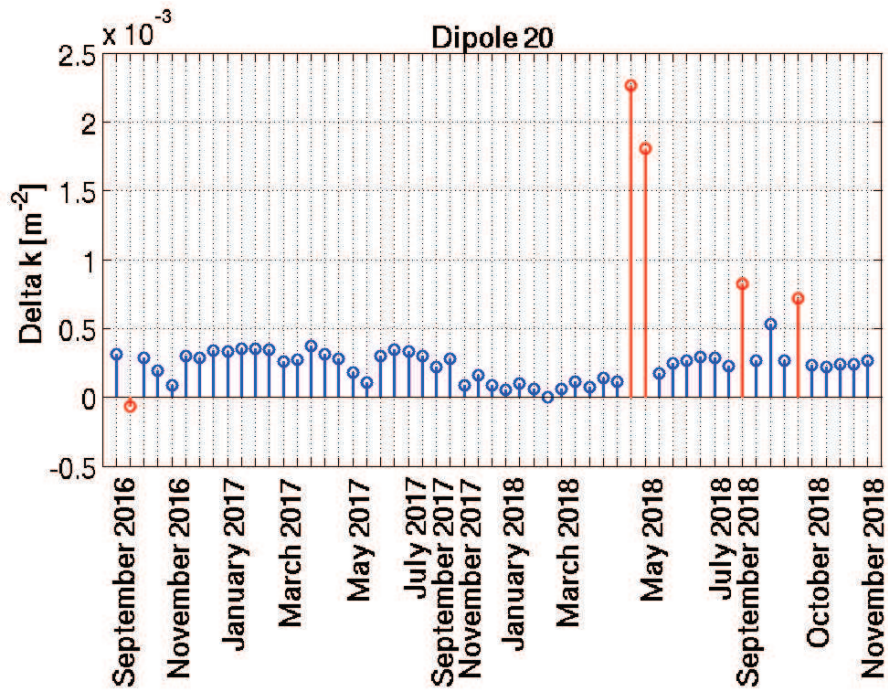
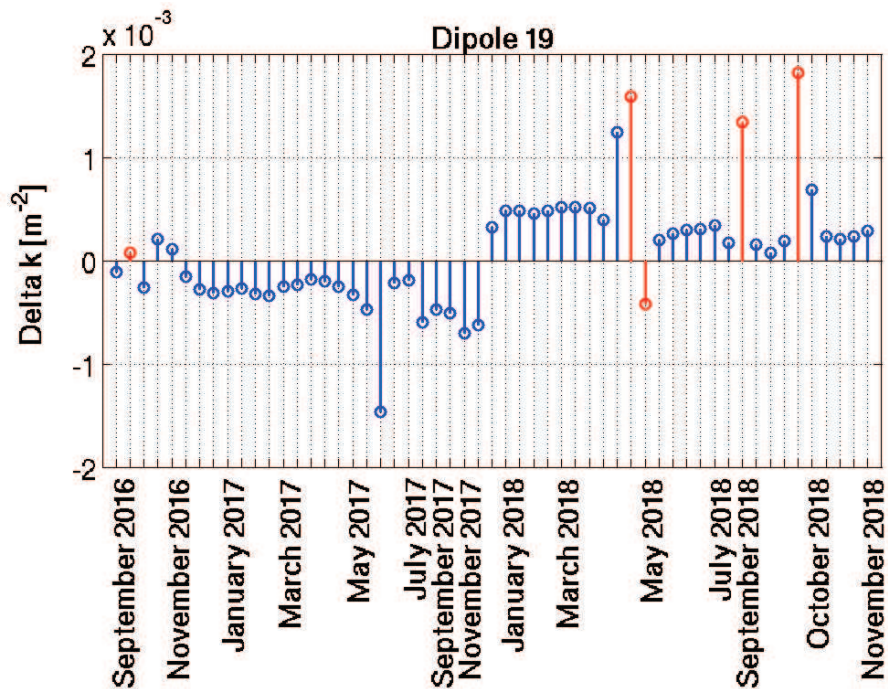


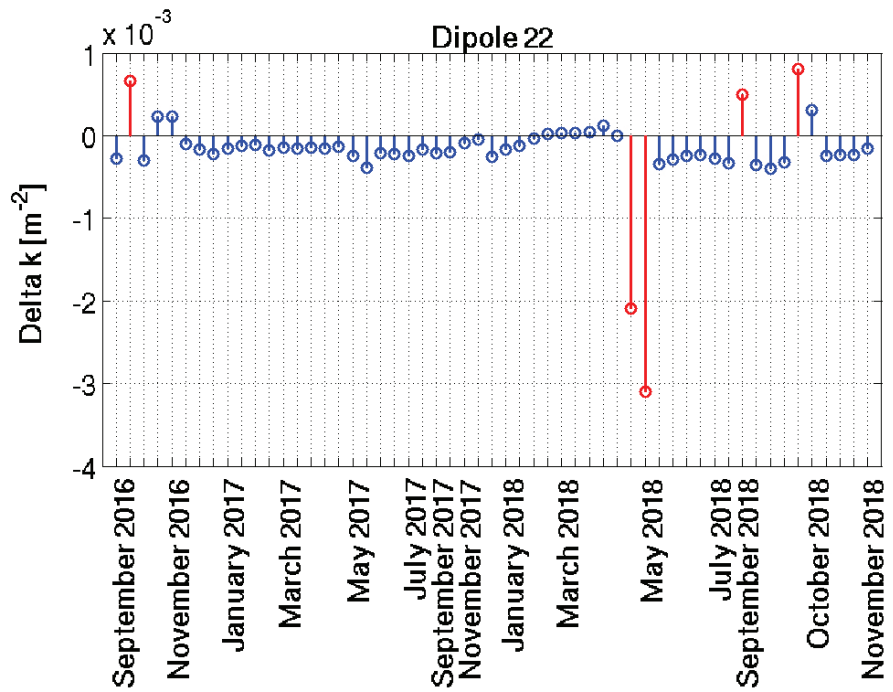
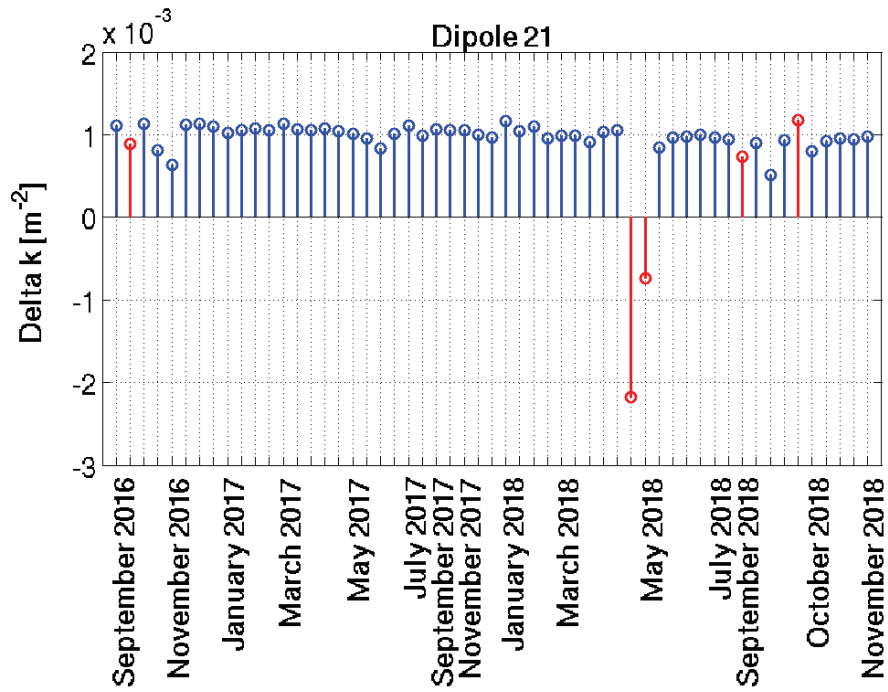


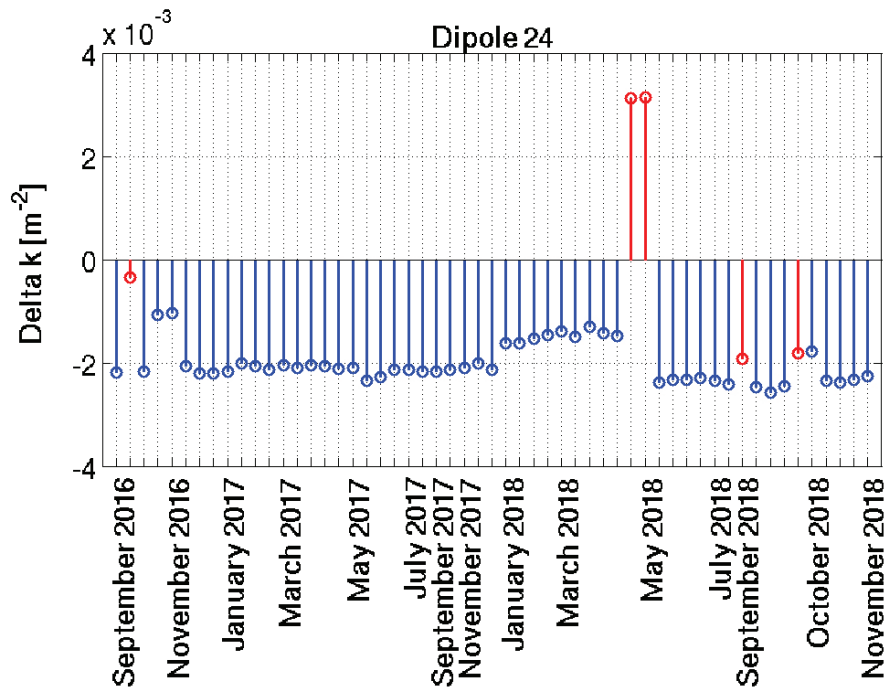
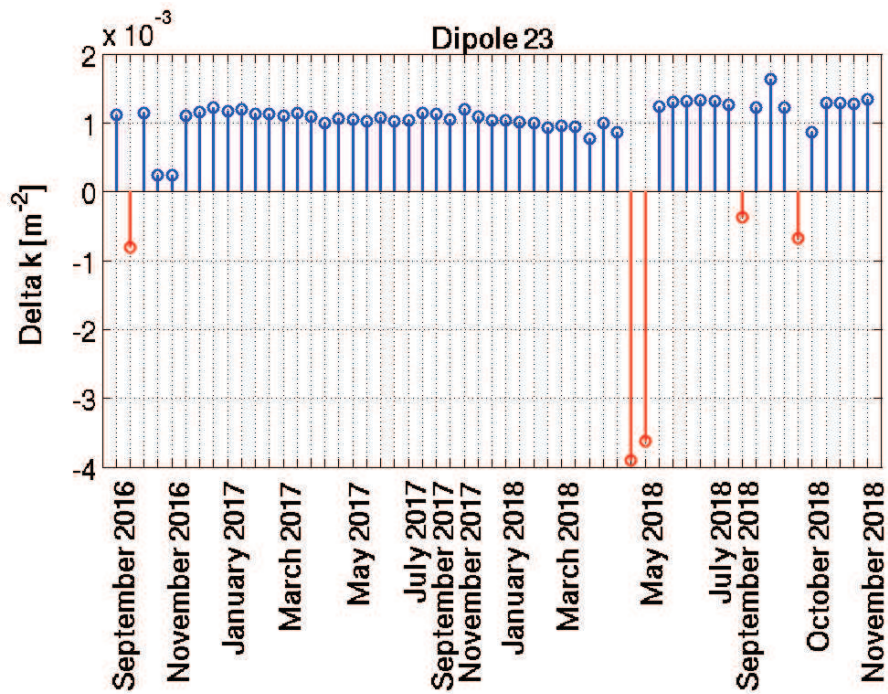


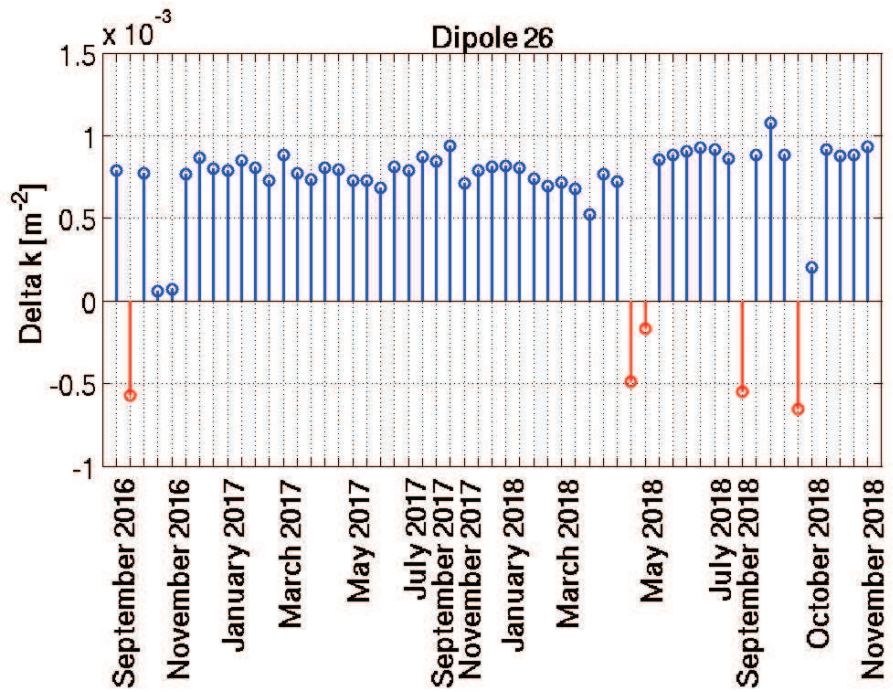
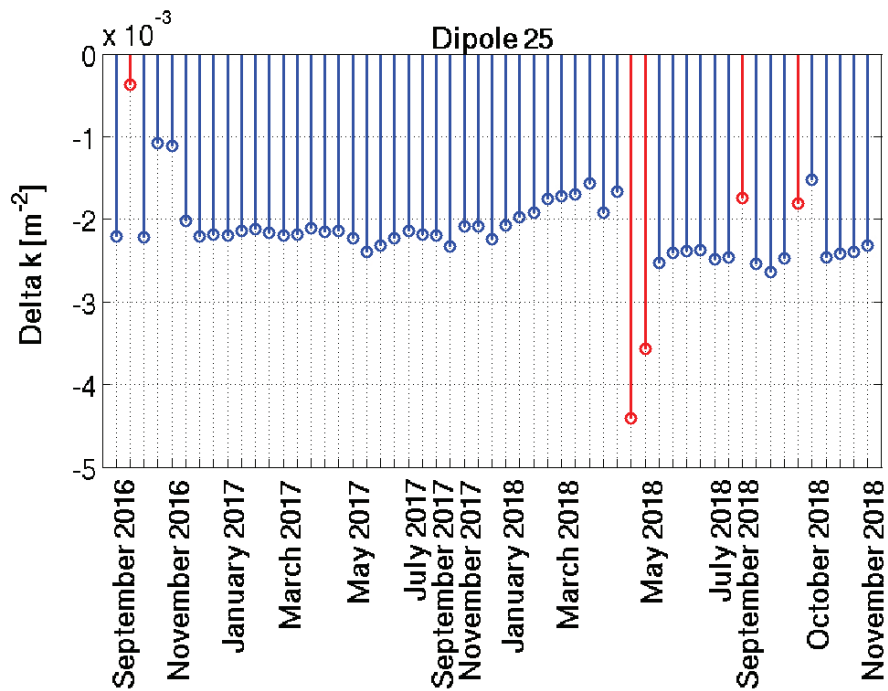


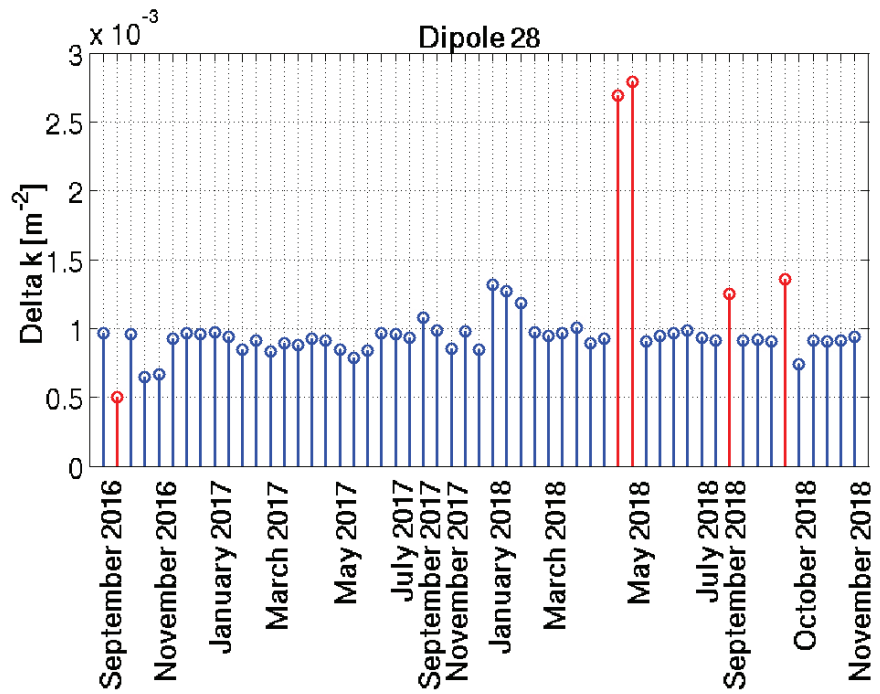
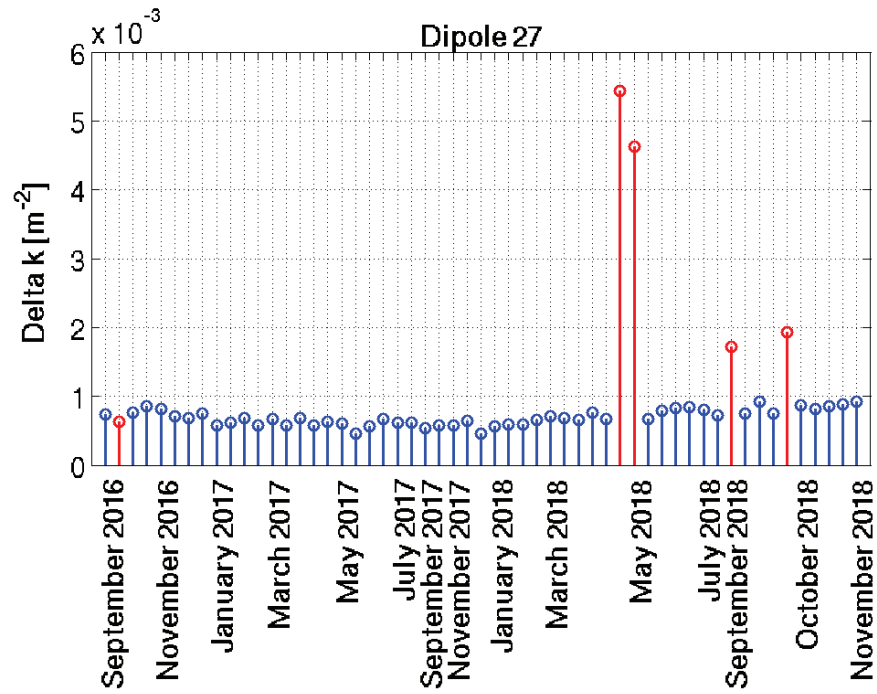


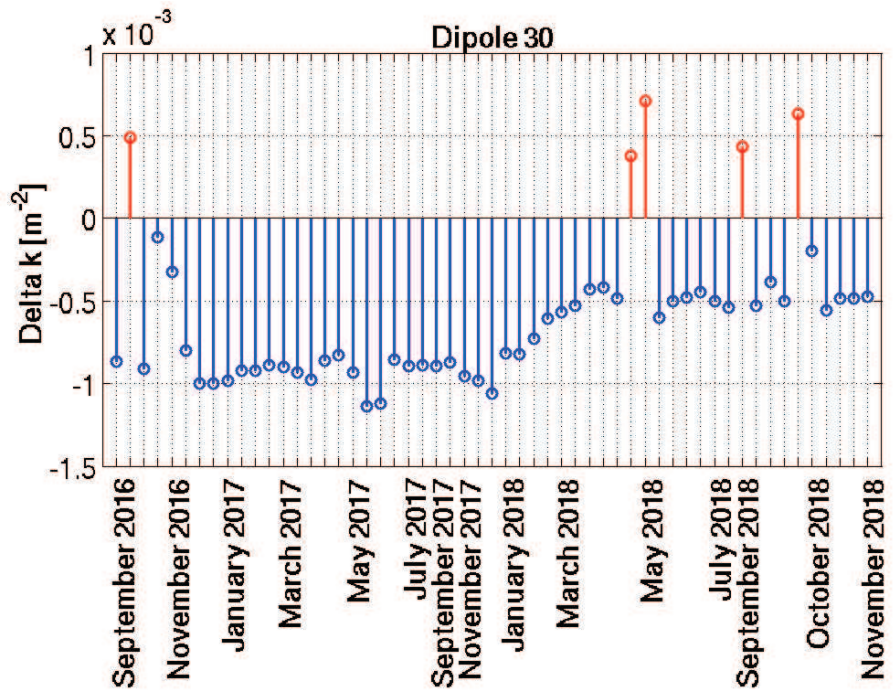
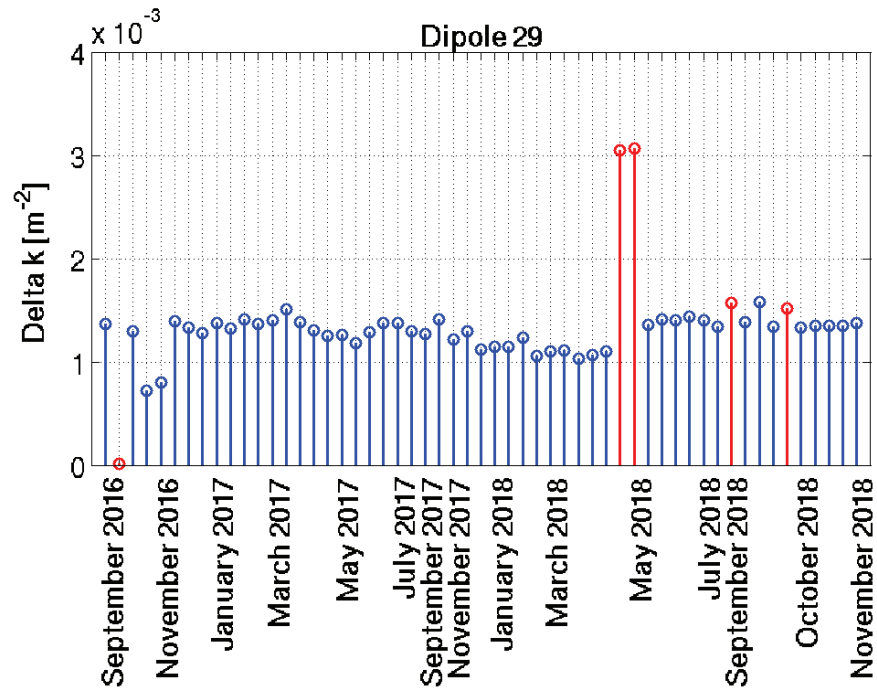


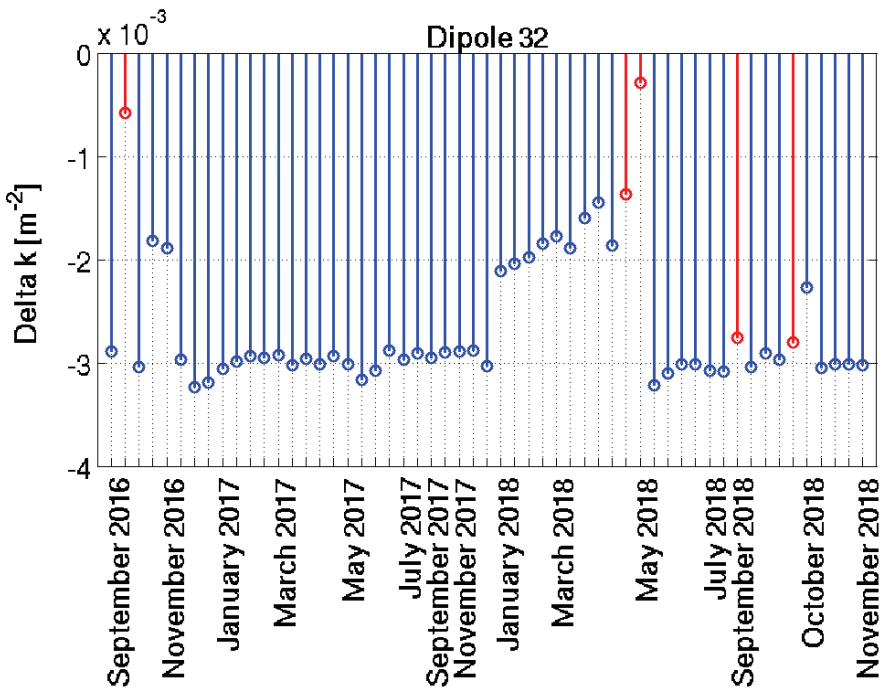
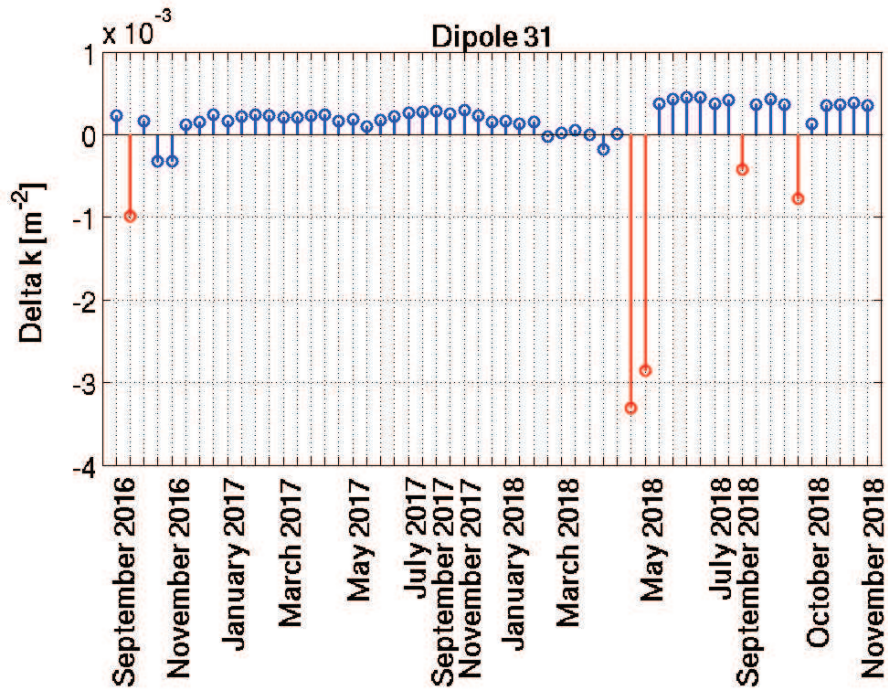






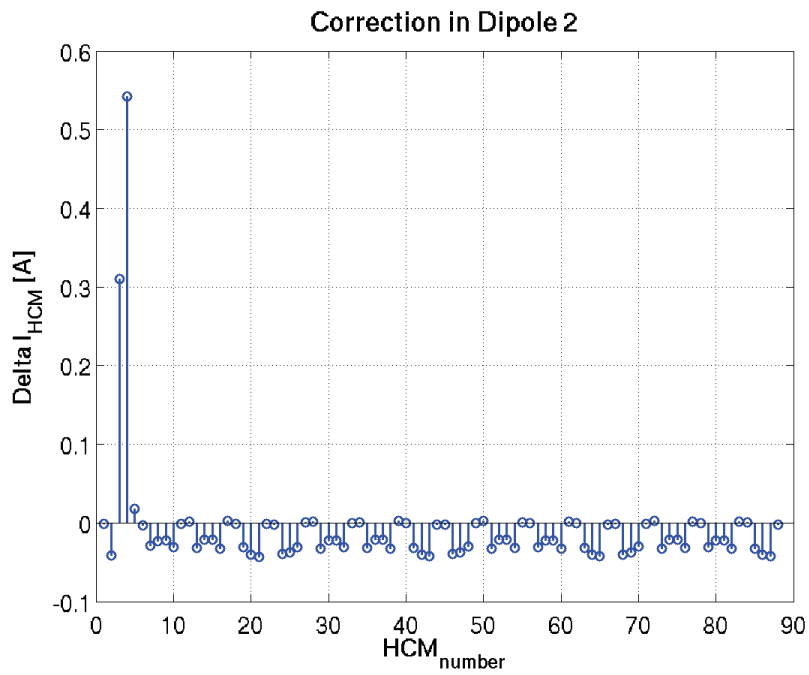
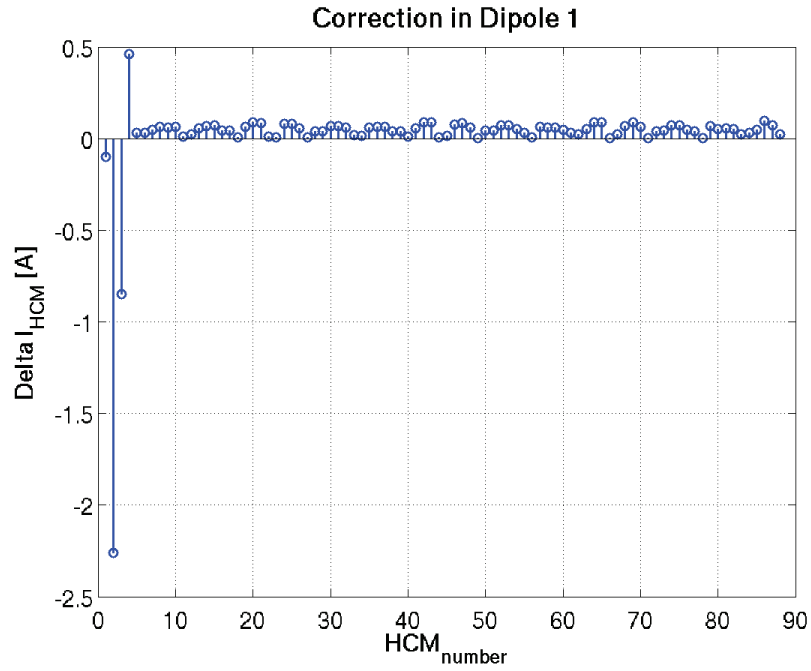


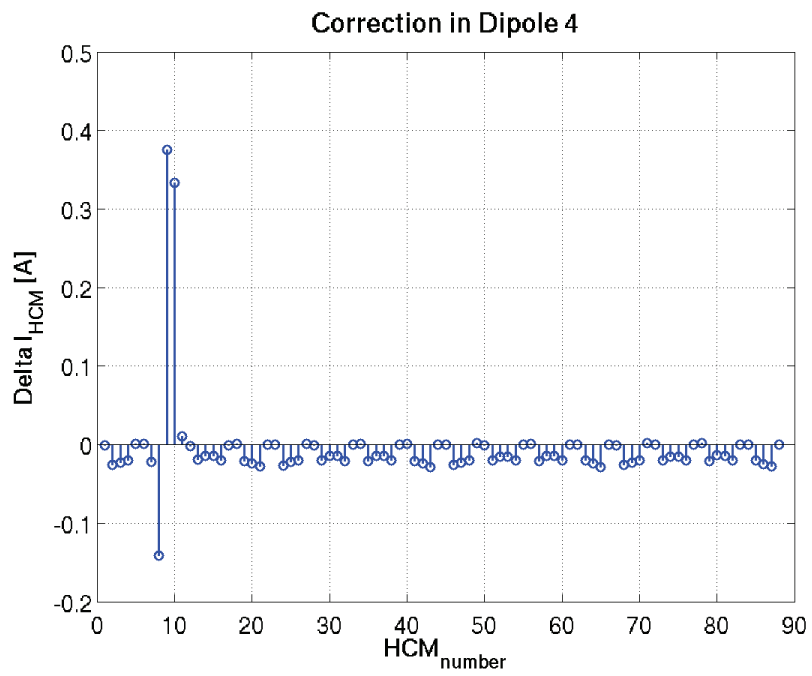
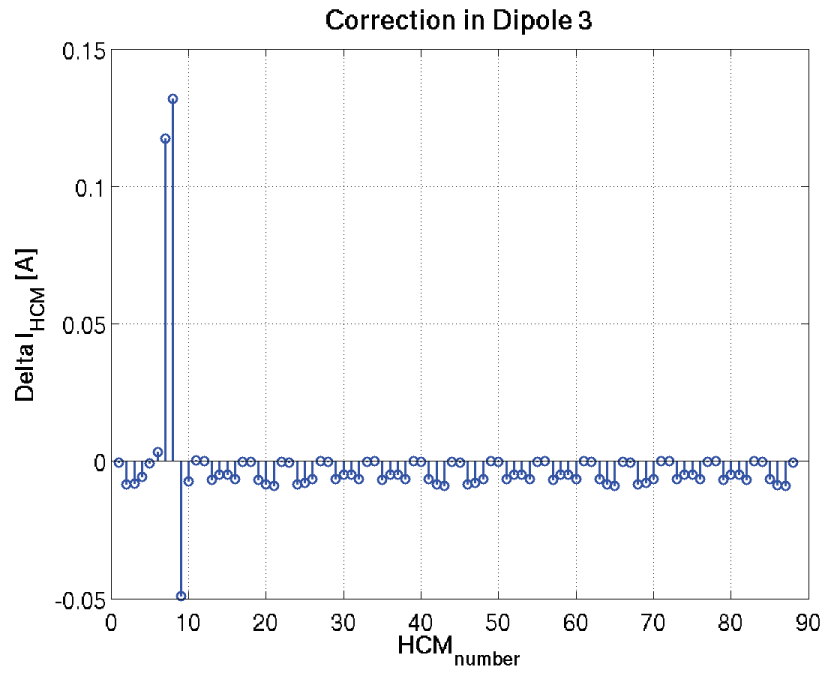




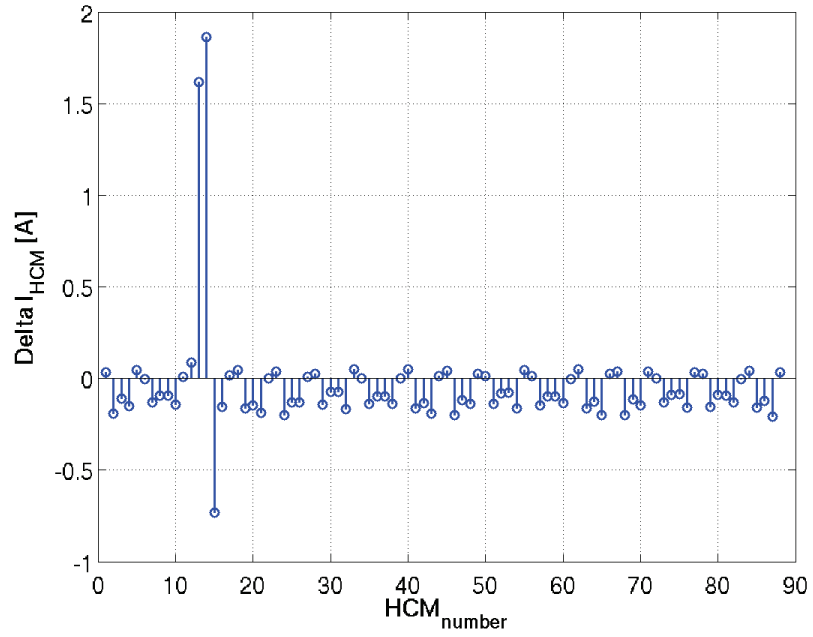
B SIMULATIONS OF THE HORIZONTAL CORRECTOR MAGNETS' ΔI

In this section there are included the 32 simulations of the horizontal corrector magnets' ΔI_{HCM} near to each dipole to compensate the field changes when applying the trim coils ΔI_{TRIM} .

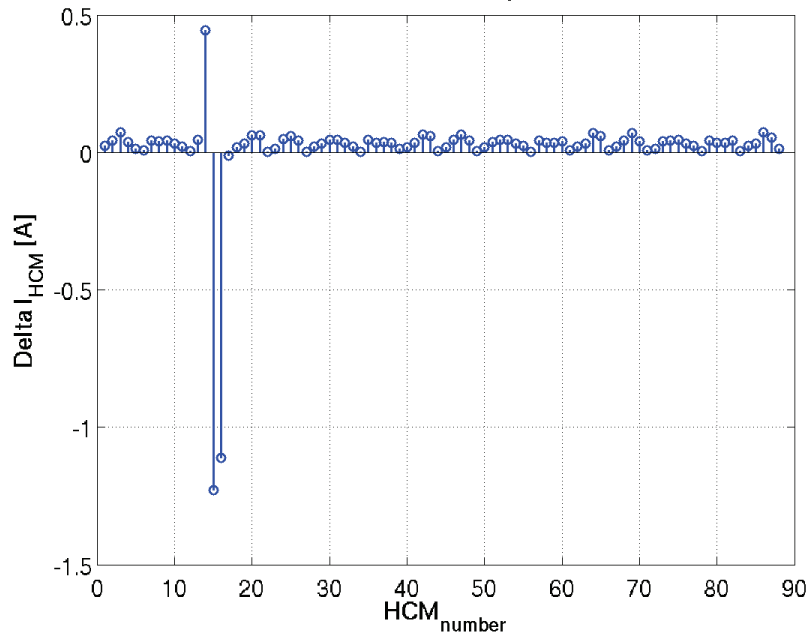


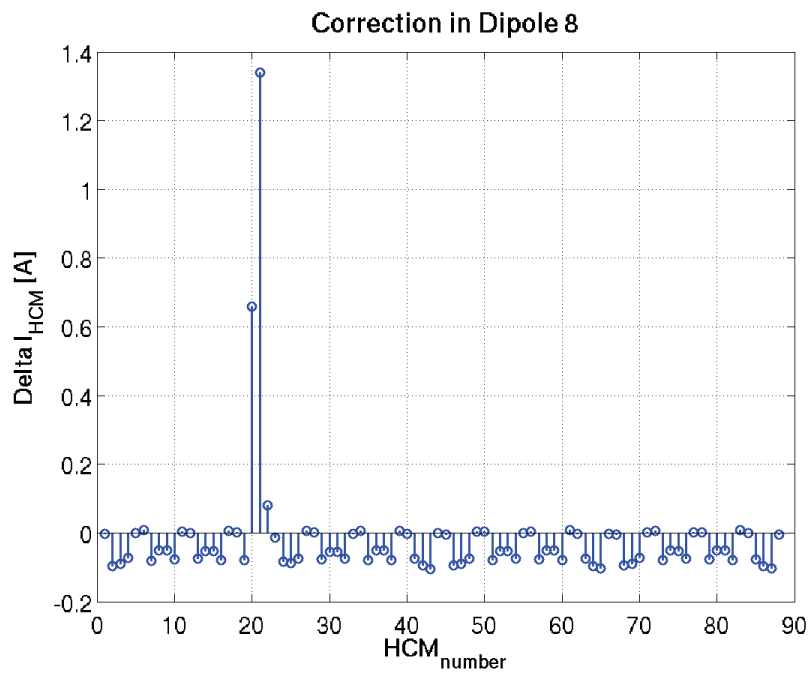
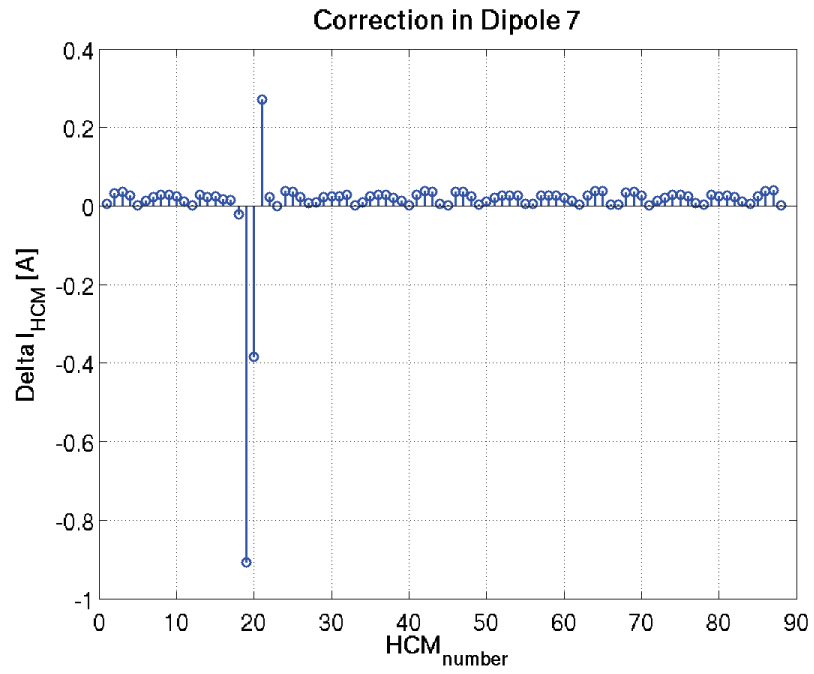


Correction in Dipole 5

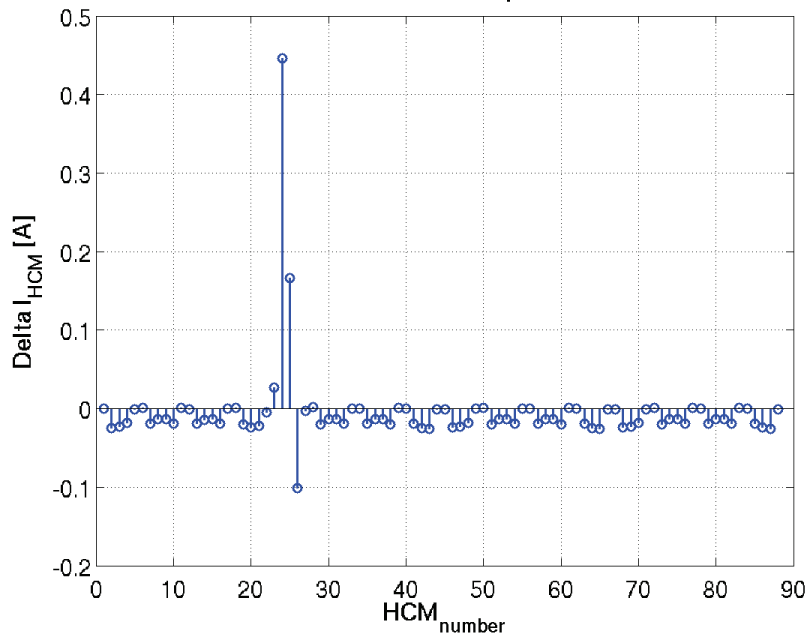


Correction in Dipole 6

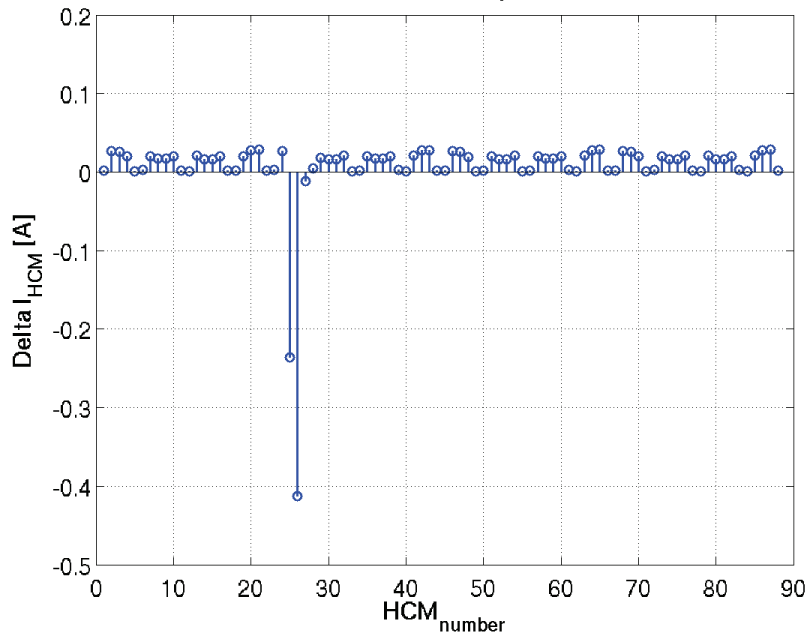




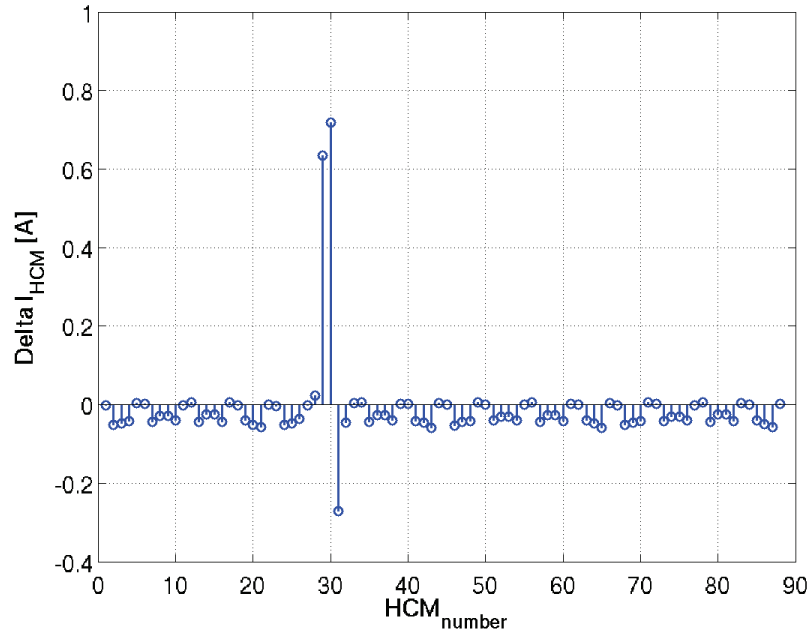
Correction in Dipole 9



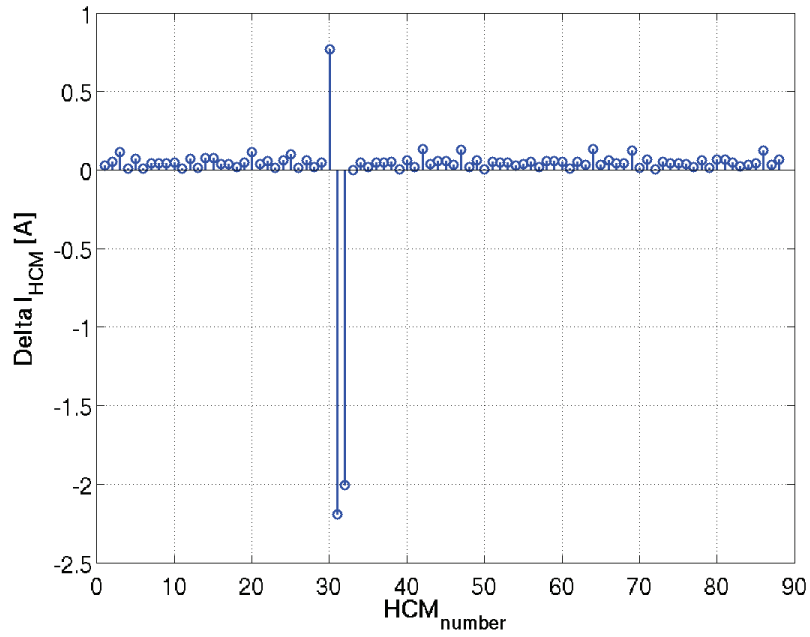
Correction in Dipole 10



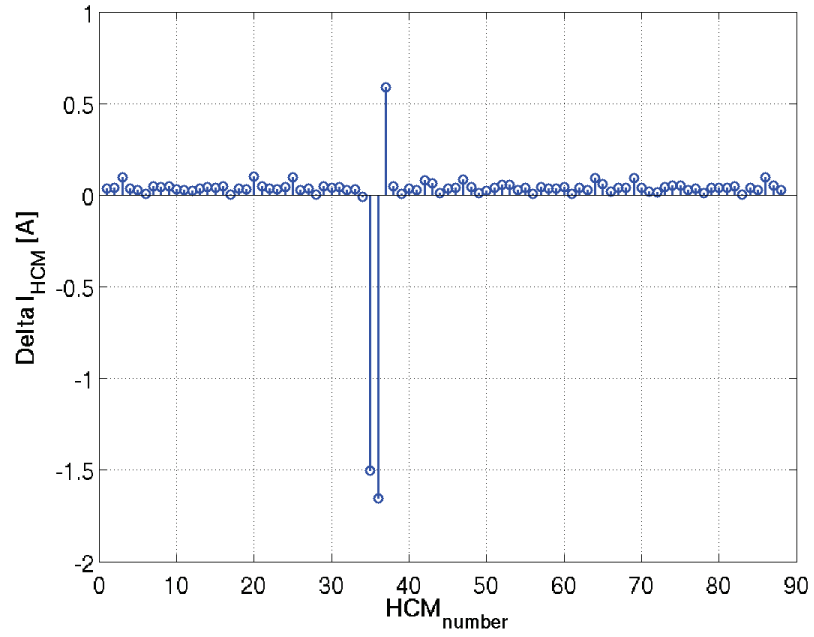
Correction in Dipole 11



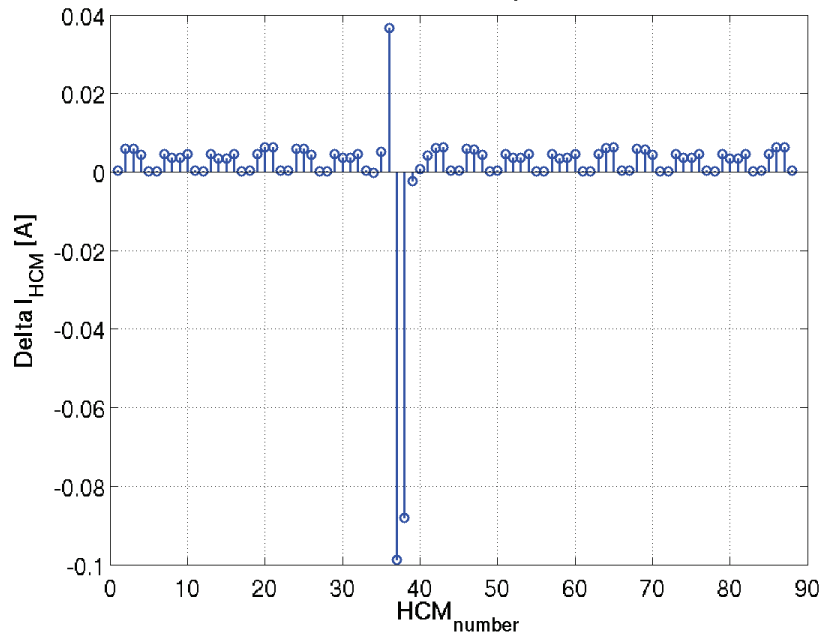
Correction in Dipole 12

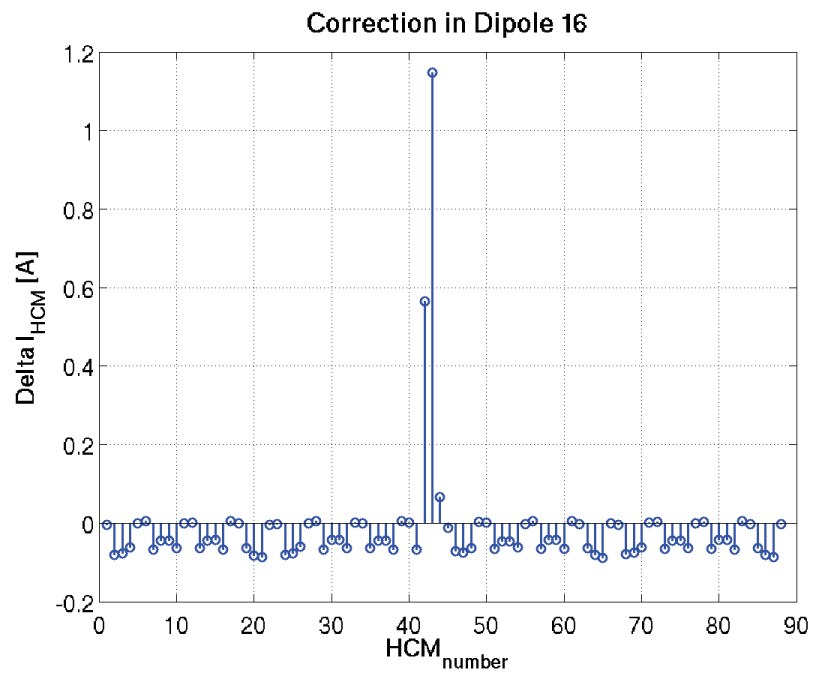
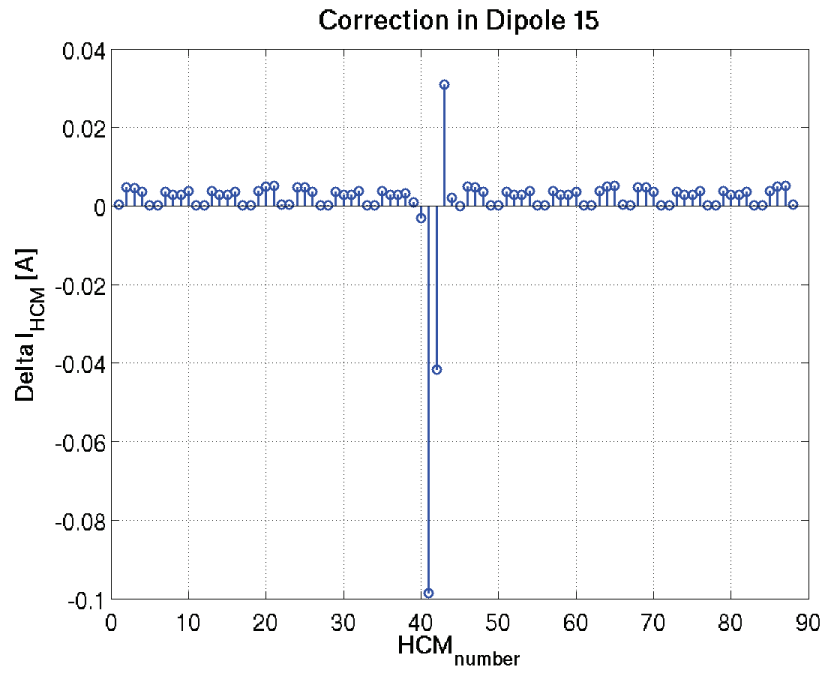


Correction in Dipole 13

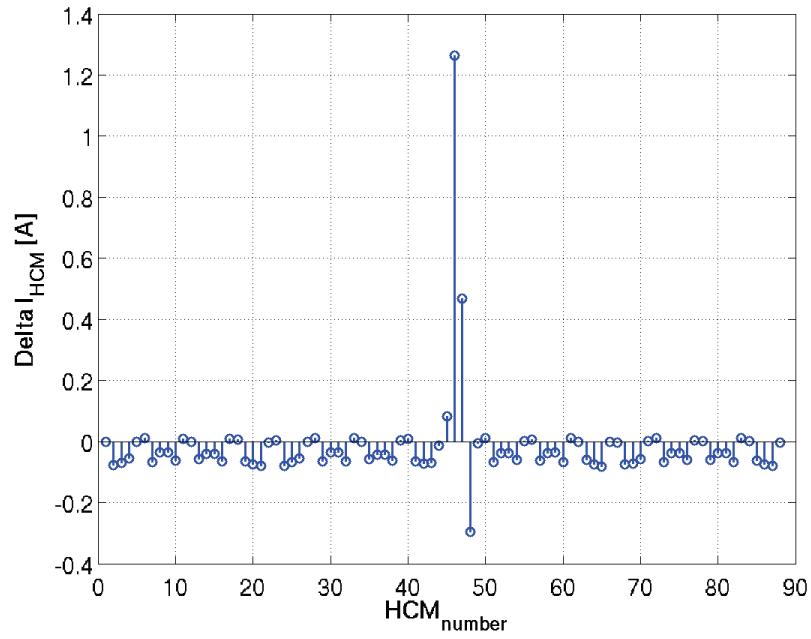


Correction in Dipole 14

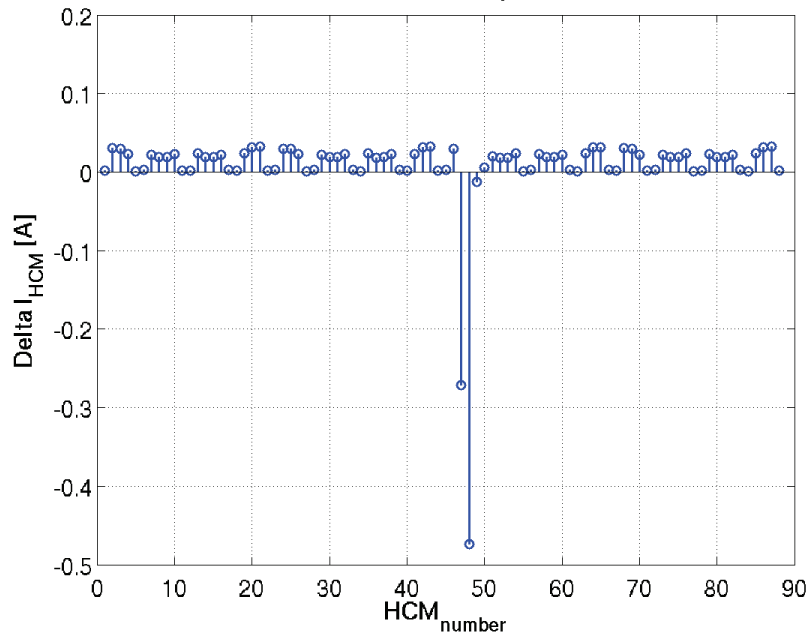




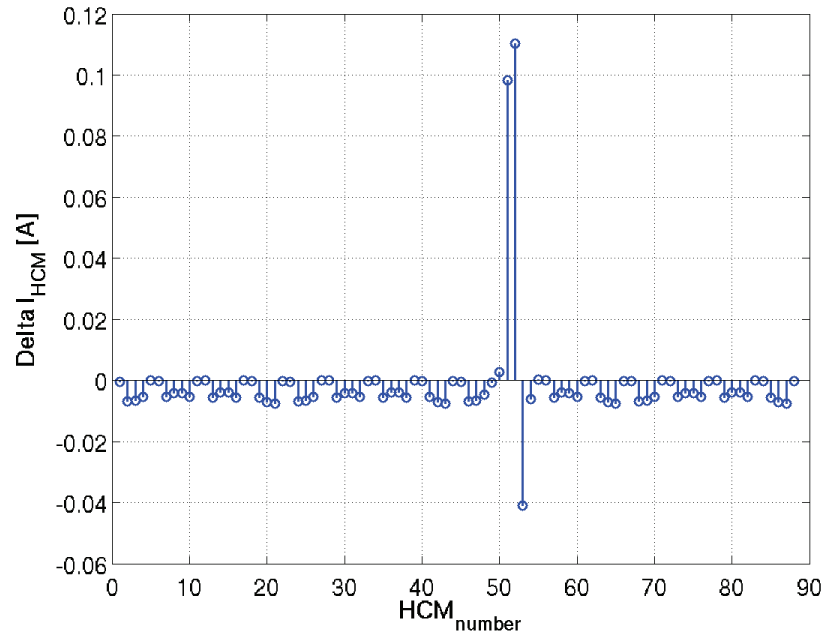
Correction in Dipole 17



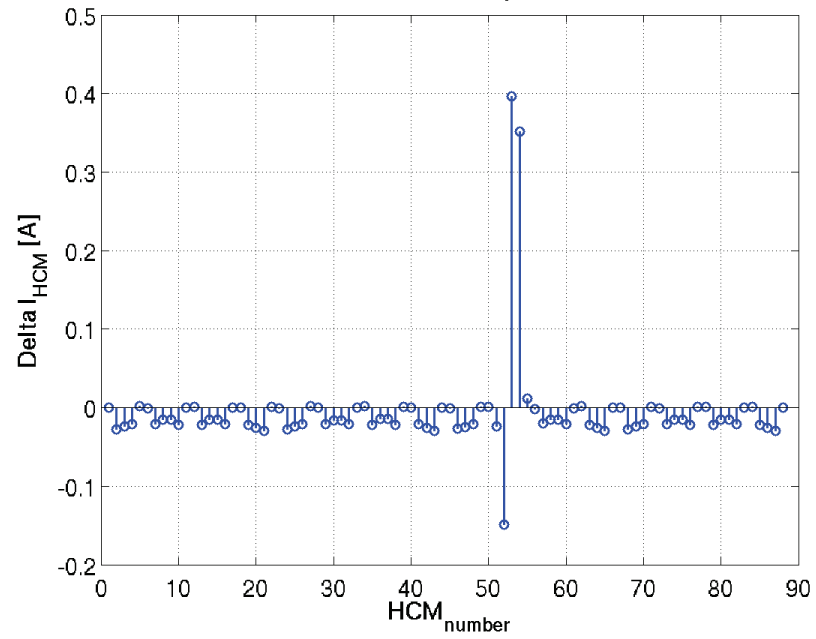
Correction in Dipole 18



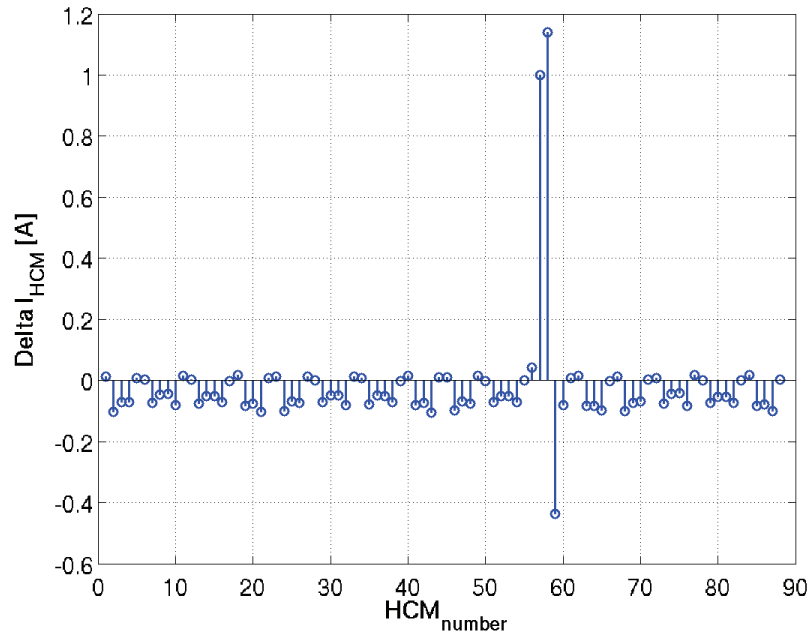
Correction in Dipole 19



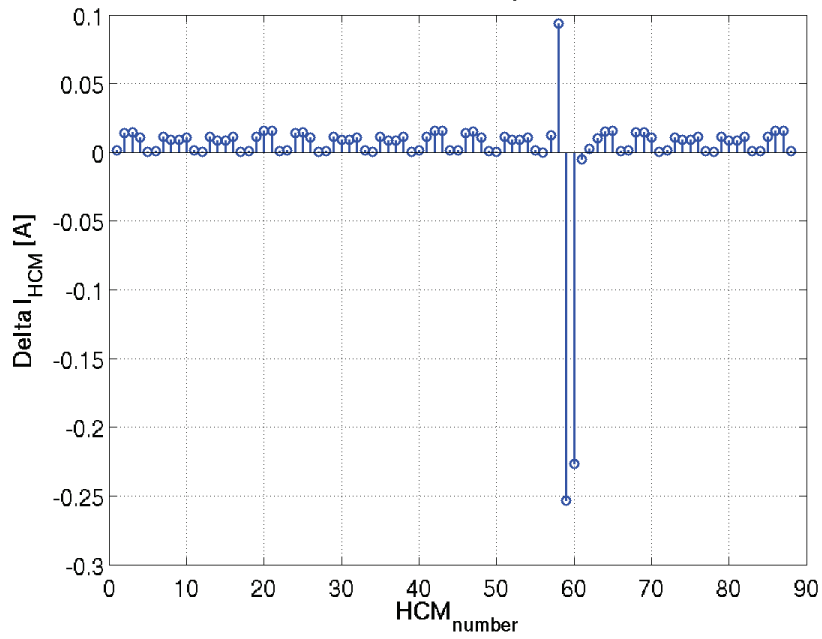
Correction in Dipole 20



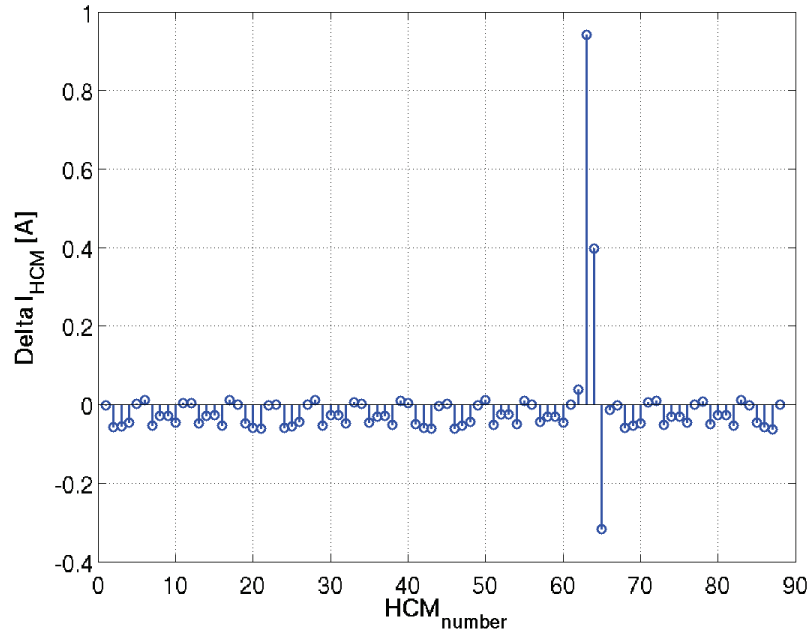
Correction in Dipole 21



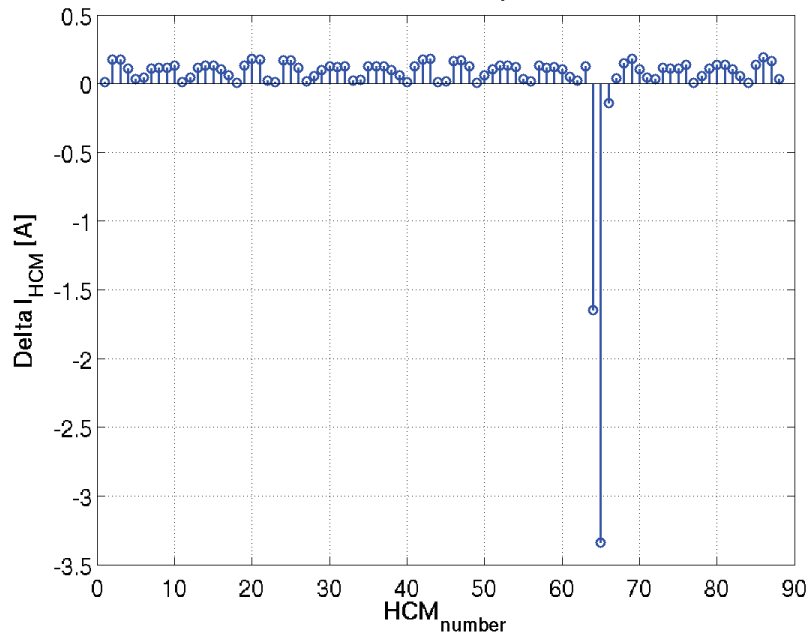
Correction in Dipole 22



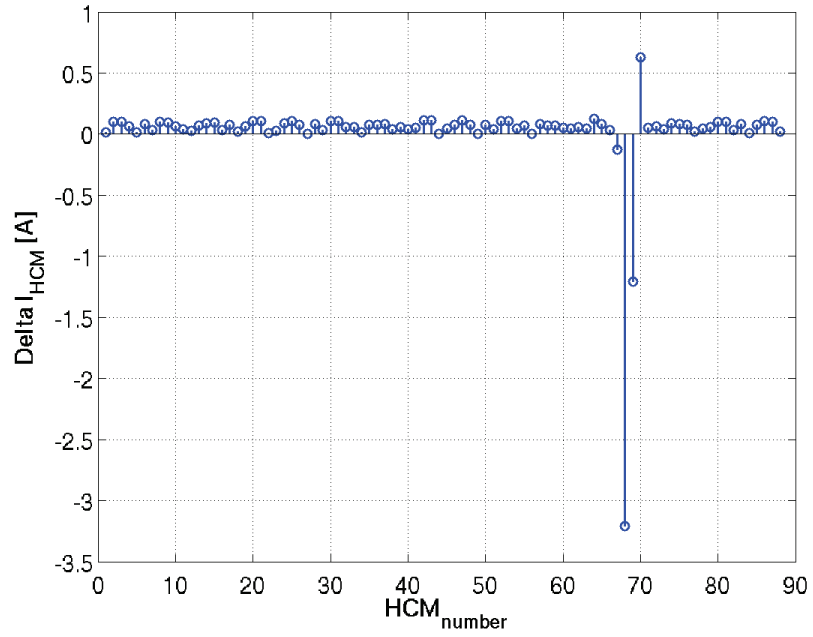
Correction in Dipole 23



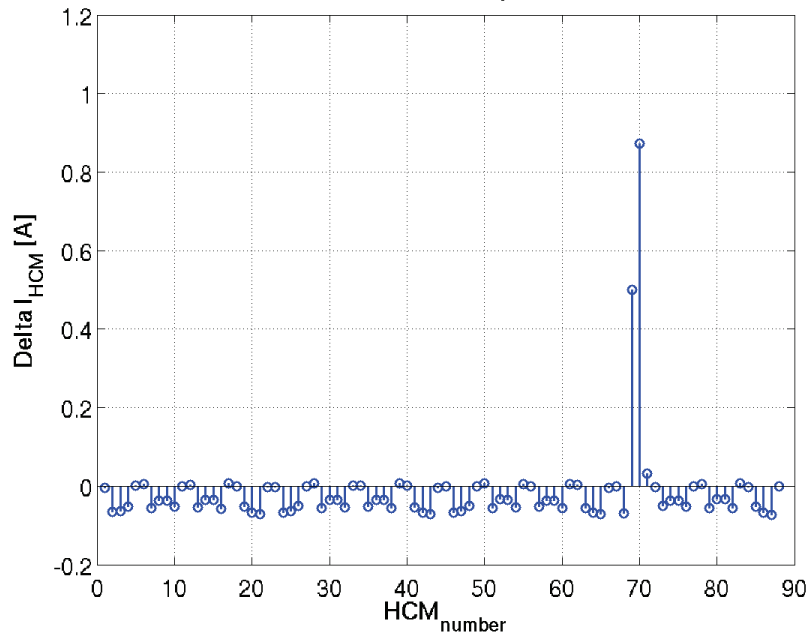
Correction in Dipole 24



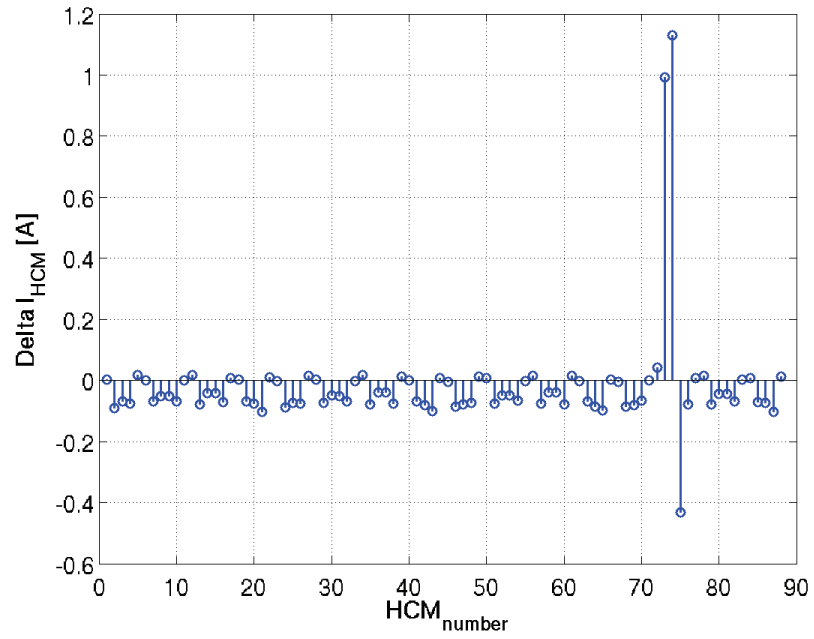
Correction in Dipole 25



Correction in Dipole 26



Correction in Dipole 27



Correction in Dipole 28

