Measurement 102 (2017) 33–41

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Long term drifts in baselines of ground magnetic observatories

Anil Iype [a,*], A.T. Deshmukh [b], B. Veenadhari [b]

[a] Geomagnetic Observatory, Indian Institute of Geomagnetism, Kalapet, 605014 Pondicherry, India
[b] Indian Institute of Geomagnetism, 410 218 Navi Mumbai, India

ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form 20 January 2017
Accepted 26 January 2017
Available online 1 February 2017

Keywords:
Long term baseline stability
Magnetic observatory
Gradient field variation
Baseline drift

ABSTRACT

The stability of baseline is the most important criterion for evaluating the data quality of a ground magnetic observatory. Theoretically, a baseline should be a straight line, provided, there are no error factors affecting the absolute instruments, the variometer and the observational procedure. But in practice, we observe that the baselines are affected by some errors in the form of random errors and long term baseline drifts. It is known that temperature, pier tilts, aging of electronic components, etc. can affect the long term stability of baselines, but in this paper we discuss a new type of error which affects the baseline in the form of long term drifts due to the variation in the gradient field between the absolute room and the variometer room. Even though, a site is selected with the least magnetic gradient for the establishment of an observatory, in many cases, it is found that the magnetic gradient patterns are not permanent and changes over the time. This slow gradient changes can distort the actual temporal magnetic variations and thus affecting the purity of data recorded at a geomagnetic observatory. We have analytically shown that an ideal baseline has to be a horizontal straight line and the RHS of the fundamental equation of an observatory should be a constant. We have further shown that baseline instabilities are caused by variation in gradient field between the absolute and variometer pillars in addition to the measurement errors from absolute observations and variometer recording. This variation in the gradient field causes long term drifts in baselines. We have derived the correction factor which can filter out the signals arising out of variation in the gradient field. Finally we present how far the data quality can be improved by applying this correction.

1. Background

The primary function of a ground magnetic observatory is to record the temporal variation of the geomagnetic field, whereas the main purpose of a ground magnetic survey is to find the spatial variations of the magnetic field. The temporal variation during the time duration of a magnetic survey has to be corrected to get a clear picture of the spatial variations. In other words the temporal variation distorts the actual picture of the spatial variation of the magnetic component over the surveyed area. Vice versa, in the case of a ground magnetic observatory, the spatial variation component of the magnetic parameter will affect the quality of temporal variation data recorded in a magnetic observatory. In this paper we discuss a new type of error which affects the baseline in the form of long term drifts due to the variation in the gradient field between the absolute room and the variometer room. Even though, a site is selected with the least magnetic gradient for the establishment of an observatory [1], in many cases, it is found that the magnetic gradient between the absolute room and variometer room is not a constant and varies over the time. These spurious variation gets added into the magnetic field recorded and can disguise itself as genuine signals thus affecting the purity of the data recorded. We have derived the correction factor which can filter the signals arising out of gradient change between the variometer room and absolute room.

Before explaining the question how the spatial variation can come into play in the working of a magnetic observatory, it may not be out of place to discuss some basics of the working of an observatory. Gauss and Weber in 1830s, introduced the absolute instruments and the variometer as the basis for the functioning of a magnetic observatory [2]. Even though magnetic observatories have made quantum leaps in technology and sophistication of the instruments [3–5], the practice of having separate housing for variometer and absolute instruments, continues till date in almost all the observatories. This is because of the fact that we are yet to develop a magnetometer which can measure continuously all the vector components of the magnetic field in absolute terms. The vector magnetometers in the variation room continuously monitor

* Corresponding author.
E-mail addresses: aniliype@iigs.iigm.res.in (A. Iype), bveena@iigs.iigm.res.in (B. Veenadhari).

http://dx.doi.org/10.1016/j.measurement.2017.01.047
0263-2241/

the variations in the components of the geomagnetic field; they do not measure the absolute magnitudes of the components. Absolute measurements of the field are made once in a day/week in a different room called absolute room. D and I are determined using a fluxgate sensor mounted on a theodolite and F is measured using a proton precession/Overhauser magnetometer. The absolute observations are used in conjunction with the variometer measurements to derive baselines and produce a continuous record of the absolute values of the geomagnetic field elements as if they had been measured at the observatory reference pillar [5,6].

2. Baselines

For every absolute measurement from the absolute room there is a corresponding delta value from the variometer during the time period of the absolute measurement. Since we are measuring the same magnetic component with two different types of instruments, i.e., the absolute and the variometer, any increase or decrease shown in the absolute value from one absolute observation to the other, the variometer will also register an exactly equal increase or decrease in the magnetic component. This is only natural because at any instance, the measured component cannot give different rate of changes just because of the fact that the mode of measurements is different. Thus for a sequence of n number of observations, we get n number of ordered pairs $(Abs_1, \Delta_1),\ (Abs_2, \Delta_2),\ (Abs_3, \Delta_3), \ldots\ldots, (Abs_n, \Delta_n)$, where Abs_i is the measured value from the absolute observations and Δ_i is the corresponding delta value. The two terms Abs_i and Δ_i are linked mutually in such a fashion that both the quantities vary together in perfect unison. It follows that if we take the difference of the first element to that of the second element of each n ordered pairs, we get a sequence of constant values. i.e., $k, k, k, \ldots\ldots\ldots, k$,

$$Abs_i - \Delta_i = k, \quad i = 1, 2, 3, \ldots\ldots, n \tag{1}$$

the plot of which gives a row of points all of which fits exactly on a horizontal line parallel to the x-axis. This line is called a baseline in the observatory parlance. The purpose of the explanations above in this section was to show that, in theory, a baseline has to be a horizontal straight line [7].

2.1. Baseline instability

The above statement holds well as long as there are no instrumental, procedural or any other type of errors involved at the absolute end or on the variometer side [5]. These utopian conditions cannot be realized in practice because of the fact that there are many errors involved in the measurement of the variation part as well as on the absolute part. Let us say that $e_{Abs}(t)$ is the measurement error from the absolute part and $e_\Delta(t)$ the measurement error from the variometer part. The terms $e_{Abs}(t)$ and $e_\Delta(t)$ are defined as a function of time t because in addition to the random spreading, there are smooth variations in the baseline which can be approximated with nth degree polynomial with time as an independent variable. So any point in the baseline, say for baseline of H component, can be defined as

$$\left(H_{Abs}^{ObsVal} - e_{Abs}(t)\right) - \left(\Delta H^{ObsVal} + e_{\Delta H}(t)\right) = H_{Baseline}^{TruVal} \tag{2}$$

where ObsVal and TruVal denotes the observed and true value of the quantity respectively.

or in other words,

$$H_{Abs}^{ObsVal} - \Delta H^{ObsVal} = H_{Baseline}^{TruVal} + e_{Abs}(t) + e_{\Delta H}(t) \tag{3}$$

Hence the baseline defined by the constant value k (Eq. (1)) gets transformed into a "base curve" defined by $k + e_{Abs}(t) + e_{\Delta H}(t)$ and this $e(t)$ factor, $(e(t) = e_{Abs}(t) + e_{\Delta H}(t))$, is the source of baseline instabilities which manifests itself in many forms such as jumps, spikes, outliers, spreading and long term drifts. It is worth noting that, in ideal case situation, the right hand side of the equality in Eq. (3), becomes a constant with $e_{Abs}(t) = 0$ and $e_{\Delta H}(t) = 0$. When measurement errors are involved,

$$H_{Abs} - H_\Delta = k + e(t), \tag{4}$$

where $e(t) \neq 0$ the right hand side of the equality ceases to be a constant and becomes a variable by virtue of the error term $e(t)$ involved. From the above discussions we see that all the measurement errors involved in the process of recording temporal variation of magnetic components in an observatory gets reflected in the baseline of that observatory. Fig. 1 shows the baseline of H component at Pondicherry magnetic observatory for a period of 5 years. Pondicherry observatory data was chosen for the study because the baseline drift was large compared to other observatories.

The baseline plot between the two arrows shown in Fig. 1 above is enlarged in Fig. 2. If we fit a 5th degree polynomial to the baseline in Fig. 2, we can resolve the baseline into two components. That is, the actual fit (Fig. 2) and the spreading part which we get as residuals of the best fit (Fig. 3).

Here we see that the spreading follows a Gaussian distribution centered at the straight line shown in the figure which is actually a 5th degree polynomial fit of the residuals. That means, if there was no drift, the mean value of the spread will give us a straight baseline as shown in Fig. 3 as stipulated by the theory. But when the drift factor also is involved, the running mean will give us a "base curve" as depicted in Fig. 2. That means the straight line we got in Fig. 3 has deformed into a curve because of this drift factor. The drift error defined as the amount of deviation of the "base curve" from the straight line, creeps into the definitive data and will disguise itself as natural geomagnetic variations. Whether we approximate these drifting by step functions or smooth spline fitting or polynomial fits, ultimately these errors are going to distort the actual temporal magnetic variations at a station. The purpose of the above discussion was to show that the drift is the major cause of concern since it affects the purity of the data especially in long term magnetic variation studies.

3. Baseline drift

The drift of modern day magnetometers is comparatively lower than those of the classical age, but even then it still remains large than the desired accuracy for analysis for which absolute accuracy of the magnetic data plays a crucial role [8]. There are certain fields of study which require only relative accuracy of the magnetic data as detailed in [5]: studies of magnetic storms, sub-storms, pulsations. Spatial surveys over a small area carried out for mineral exploration may often need only relative accuracy. But absolute accuracy is required for a wide variety of scientific investigations: studies of secular variation, main field morphology, fluid flow in the core; long-term external field variations, from Sq to solar cycle, to name a few. Hence the baseline error noise has to be at least one order less than the long period weak signals or else aliasing can occur and will lead to spurious information and results.

With the advent of magnetic satellite observatories, the ground magnetic observatories may be at risk of losing some of their perceived relevance [9], Peltier and Chulliat [10] has pointed out that, it is important that they provide data with similar quality and timeliness as satellites. The observatory data and satellite data are complementary to each other and there are many research papers which compare ground and satellite magnetic data to study many aspects of geomagnetism [11,12]. Hence it is very essential that we should be able to address the issues of the errors like drifts which contaminate the data quality of ground magnetic observato-

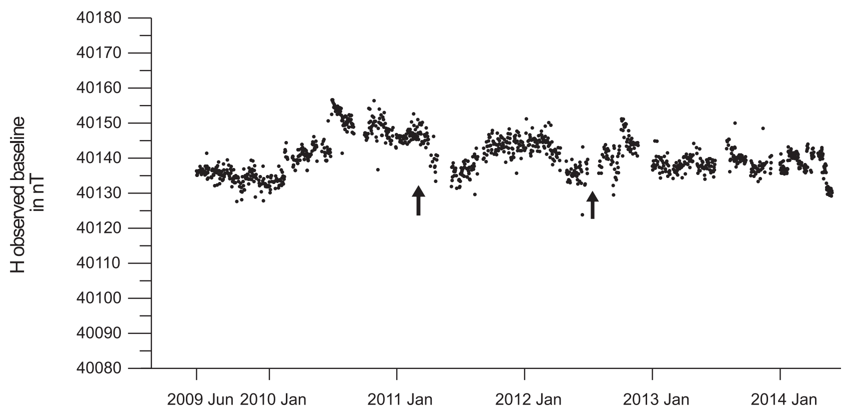

Fig. 1. 5 Years observed H baseline of Pondicherry observatory from June 2009 to June 2014.

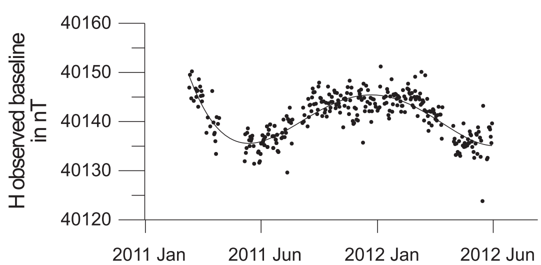

Fig. 2. The polynomial fit for the portion of the baseline between the two arrows in Fig. 1.

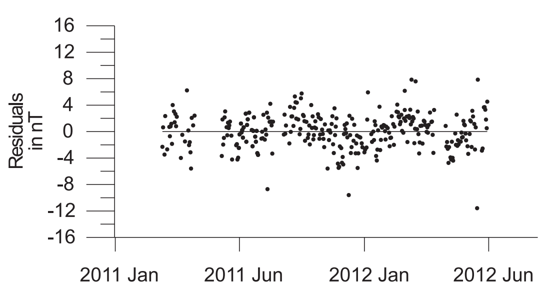

Fig. 3. The residuals of the polynomial fit shown in Fig. 2 and the 5th degree polynomial fit of the residuals.

ries [13]. This is the reason why many authors have studied and analyzed the drift problem in baselines from different perspectives [14,15]. The intermagnet specifies a maximum limit of 5 nT/yr for long term drift in baseline for the participating observatories. The baseline drift can happen due to many factors and in the following section we will discuss the different causes of baseline drifting.

3.1. Instrumental drift

The classical magnetometers were wrought with drifting mainly due to pillar tilts and temperature variation and the classical magnetometers before the Bobrov quartz type, had the additional cause for drifting because of the slow drift in the constants of the variometer, such as the moment of the magnet, scaling factor and the fiber constant [16]. With the advent of the digital era, the variation magnetometers became compact to the extent that it could be suspended to circumvent the problem of pillar tilts [17,18]. The suspended magnetometers solved the problem of drifting due to pillar tilts but the drifting due to the rotation of the sensor due to the twisting of pillar still pose a problem in some observatories [5].

To overcome drifting of those classical age instruments due to temperature effect, a temperature coefficient of the variometer was used to reduce the baseline to a standard temperature. An incorrect temperature coefficient will cause a seasonal drift in the baseline value, but this drift due to temperature can easily be detected and corrected unlike the other drifts which are not regular in time and therefore unpredictable. In the modern day digital magnetometers, the temperature may affect the coil characteristics, temperature differences may cause strain on the mechanical system and may also affect electronic components. The drift due to temperature was largely contained by using superior materials such as Macor and ceramic glass for the compensating coil and with temperature stabilization of the variometer room, but we still find some drifting because of the aging of sensor windings and the electronics involved in the magnetometers [21,19].

Variation measurements of geomagnetic field at an observatory are mostly carried out by triaxial vector fluxgate magnetometer (for measuring the variations of three orthogonal components of the geomagnetic field); a scalar magnetometer for measuring the absolute total field intensity, a theodolite mounted with a single-axis fluxgate vector magnetometer for measuring the absolute angles of Declination and Inclination [20].

Suspended type Triaxial fluxgate magnetometers are the standard instrument for measuring the variation field at an observatory worldwide. It gives a very good long term drift stability (<3 nT per year) compared to the earlier unsuspended ones. The recent development of small Overhauser sensors (<250 mm diameter) made it possible for it to be used in dIdD (delta Inclination and delta Declination) and dIdD is increasingly being used in observatories by replacing the fluxgate magnetometers. The suspended type dIdD gives better stability in long term drift with absolute accuracy of 0.2 nT and a resolution of 0.01 nT.

The discovery of Overhauser effect and the subsequent application of the same in magnetometer helped in fabrication of scalar magnetometers which are smaller in size and with lesser power consumption. Taking advantage of the transfer of nuclear spin polarization of unpaired electrons to the hydrogen atom with the help of radio frequency magnetic field, the system generates a strong precession signal. Using of RF has the advantage of consuming minimum power and high sampling rate. The latest addition of magnetometers for geophysical applications are the optically pumped magnetometers. Potassium and Cesium magnetometers are commercially available and are rugged enough for field use. The advantage over overhausser magnetometer is the high resolution of 0.0001 nT and absolute accuracy $\pm$0.05 nT with a maximum sampling rate of 20 Hz. The instruments we use at Pondicherry observatory are FGE-FGM Triaxial fluxgate magnetometer with 0.1 nT resolution, DI-Flux single axis fluxgate magnetometer

Mag-01H (produced by Bartington Instruments) with a resolution of 0.1 nT. Scalar magnetometer GSM-90 overhausser magnetometer of GEM systems.

3.2. Gradient drift

The discussions in the previous section were on the drift due to measurement and instrumental errors. In this section we will discuss about a drift mechanism which is different from the above. While selecting a site for the establishment of an observatory, it is a normal practice to choose a site with minimum magnetic gradients, preferably with less than 1 nT/m gradient [22]. But in the case of many observatories, this criterion could not be satisfied because of many constraints and other factors and the gradients at these observatories can be higher than the desirable limit. The gradients in the magnetic field between the pillars can be due to many reasons such as crustal field contributions, inhomogeneous electrical conductivity distribution in the ground and from local magnetized rocks and soil. That means the F value at the absolute pillar need not be the same as at that of the variation pillar and when we take the difference of these two Fs, we expect to see a constant offset. But we have increasing body of evidence from many observatories that this difference need not be a constant. This can contribute a gradient drift in the baseline. This type of error due to spatial variation can be avoided if we have a magnetometer which can measure continuously all the vector components of the magnetic field in absolute terms. Since no such instruments exist, we continue the tradition of having two separate rooms for absolute magnetometer and for the variation magnetometer. To derive baselines and produce a continuous record of the absolute values of the geomagnetic field elements, as if they had been measured at the observatory reference pillar (absolute pillar), we use the following, the fundamental magnetic observatory relationships between absolute (D, I, F) and variometric measurements $(\Delta D, \Delta H, \Delta Z)$ as given in JL Rasson [23] 2005

$$H^{AR}_{Abs} = H^{AR}_{BL} + H^{VR}_{\Delta} \tag{5}$$

The superscripts indicates the room at which the component is measured ie., AR and VR represents absolute room and variometer respectively. The subscripts denotes the mode of measurement. ie., Δ, Abs and BL denotes variation measurement, absolute measurement and baseline respectively. To overcome the problem of gradient drift error, let us assume that both variometer and absolute magnetometer are fixed on the same pillar in the variometer room.

In such an ideal condition

$$H^{VR}_{Abs} = H^{VR}_{BL} + H^{VR}_{\Delta} \tag{6}$$

The H in the above equation can be rewritten in the form of $FCos(I)$,

$$F^{VR}_{Abs}Cos(I) = F^{VR}_{BL}Cos(I) + H^{VR}_{\Delta} \tag{7}$$

The above equation may be valid theoretically but practically the triaxial fluxgate variation magnetometer, absolute DIflux and the Proton magnetometer cannot be kept on a single pillar because of cross talk and mutual interference [21]. But when we keep these instruments at a safe distance from each other, the spatial variation in F value come into play.

3.3. Drift correction factor

Let the difference between F at absolute pillar and that of variation pillar be dF.

$$F^{AR}_{Abs} - F^{VR}_{Abs} = dF$$

$$ie., \quad F^{VR}_{Abs} = F^{AR}_{Abs} - dF \tag{8}$$

Substituting the above relation of dF in Eq. (7) will give us,

$$\left[F^{AR}_{Abs} - dF\right]Cos(I) = F^{VR}_{BL}Cos(I) + H^{VR}_{\Delta} \tag{9}$$

In Eq. (9), interchanging the second terms on both sides of the equality,

$$F^{AR}_{Abs}Cos(I) - H^{VR}_{\Delta} = F^{VR}_{BL}Cos(I) + dFCos(I) \tag{10}$$

Taking out the common term $Cos(I)$ in RHS,

$$F^{AR}_{Abs}Cos(I) - H^{VR}_{\Delta} = \left(F^{VR}_{BL} + dF\right)Cos(I) \tag{11}$$

Since we have already defined that the difference in F between variometer room and absolute room is dF, the following statement

$$F^{VR}_{BL} + dF = F^{AR}_{BL} \tag{12}$$

holds and so, Eq. (11) becomes

$$F^{AR}_{Abs}Cos(I) - H^{VR}_{\Delta} = F^{AR}_{BL}Cos(I) \tag{13}$$

i.e.,

$$H^{AR}_{Abs} - H^{VR}_{\Delta} = H^{AR}_{BL} \tag{14}$$

This is the equation which we use to obtain baselines in observatories. We started with an ideal situation (Eq. (6)) and ended up with the traditional equation (Eq. (14)) but in the process we have shown that the RHS, H^{AR}_{BL} in Eq. (14) is actually the sum of two terms. i.e., $F^{VR}_{BL}Cos(I)$ and $dFCos(I)$. So we can rewrite Eq. (14) as

$$H^{AR}_{Abs} - H^{VR}_{\Delta} = F^{VR}_{BL}Cos(I) + dFCos(I) \tag{15}$$

We have seen earlier that the theory stipulates that the RHS of Eq. (15) should be a constant. That means each of the constituting terms on RHS of Eq. (15) has to be a constant. Since the $dFCos(I)$ term is the one which represents the gradient error factor, in the light of the preceding statement, to check for the role of gradient error in the baseline instability, we only need to check whether this term remains a constant over time or not. The following figure shows the plot of dF of Pondicherry Observatory.

We observe in Fig. 4 that the term dF is not a constant. The pattern of H baseline instability in Fig. 1 shows a striking resemblance with that of the pattern of dF variation. The scatter plot between the H Baseline and dF in Fig. 5 below shows a linear correlation between the two.

From the above plot it is very clear that dF between the absolute Pillar and the variation pillar is varying over time and this error plays a dominating role in the H baseline inconsistency. The above discussions and figures point to the fact that there is one more source of error for the baseline instability in addition to those errors described in Eq. (3). So the equation of baseline instability Eq. (3) gets modified into

$$H^{ObsVal}_{Abs} - \Delta H^{ObsVal} = H^{TruVal}_{BL} + e_{AbsH}(t) + e_{\Delta H}(t) + e_{dF_{Drift}}(t) \tag{16}$$

or in general, for the magnetic component B,

$$B^{ObsVal}_{Abs} - \Delta B^{ObsVal} = B^{TruVal}_{BL} + e_{AbsB}(t) + e_{\Delta B}(t) + e_{dF_{Drift}}(t) \tag{17}$$

where $e_{dF_{Drift}}(t)$ represent the gradient drift error. Now we will see how to correct this problem of gradient drift affecting the baseline consistency. We again invoke the ideal condition theory which insists that the right hand side of the RHS in Eq. (15) has to be a constant. As we see that the dF in Fig. 4 has a constant part and a variation part. The constant part can be taken as the mean value and the variation part is the deviations from this constant mean value, we can rewrite dF as

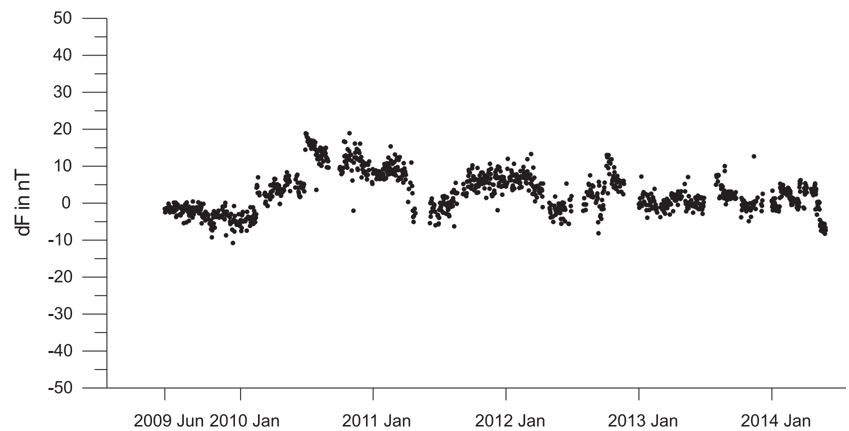

Fig. 4. The plot of *dF*.

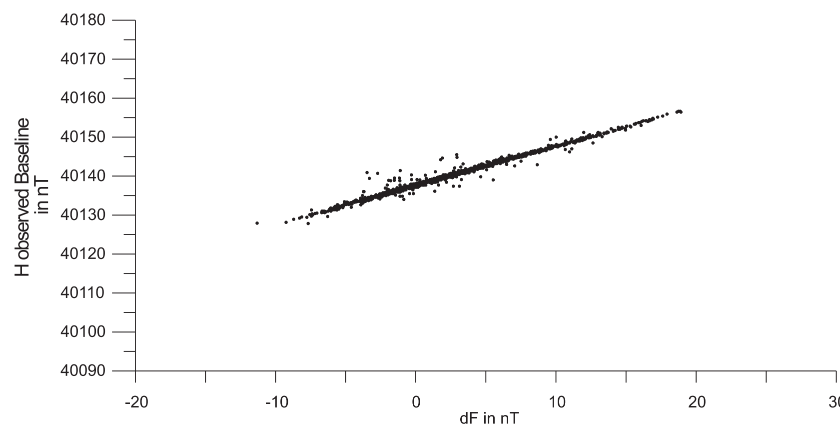

Fig. 5. The scatter plot between *H* baseline and *dF*.

$$dF = dF_{Cons} + dF_{Var} \tag{18}$$

In the case of Pondicherry observatory, this becomes,

$$dF = 3.1nT + (dF - 3.1nT) \tag{19}$$

The splitting of dF into variation part and constant part needs some explanation. Since we are adding a constant value and subtracting the same in Eq. (19), we are not disturbing the system. So we have the choice to use any arbitrary value, but we are bound by the constraint that it should not introduce a large constant offset in the baseline. So we should go for the value which will give zero offset or at least for a minimum possible baseline offset. In our case we used the mean of dF for a period of five years and arrived at the value of 3.1 nT. So let us substitute Eq. (19) in Eq. (15),

$$H^{AR}_{Abs} - H^{VR}_{\Delta} = H^{VR}_{BL} + (dF_{Cons} + dF_{Var})Cos(I) \tag{20}$$

Taking the variation part in RHS to the LHS and retaining only the constant part on the RHS, we get

$$H^{AR}_{Abs} - H^{VR}_{\Delta} - dF_{Var}Cos(I) = H^{VR}_{BL} + dF_{Cons}Cos(I) \tag{21}$$

Here $dF_{Cons}Cos(I)$ is nothing but $dH_{Constant}$. That is the difference of H component between the absolute and variometer pillar.

$$H^{AR}_{Abs} - H^{VR}_{\Delta} - dF_{Var}Cos(I) = H^{VR}_{BL} + dH_{Cons} \tag{22}$$

This dH_{Cons} added with H^{VR}_{BL} will give H^{AR}_{BL} ie.,

$$H^{AR}_{Abs} - H^{VR}_{\Delta} - dF_{Var}Cos(I) = H^{AR}_{BL}. \tag{23}$$

Here we see that $-dF_{Var}Cos(I)$ is the correction factor for H for gradient drifts. When the difference in F between variometer and absolute room does not vary, ie., dF_{Var} becomes zero, we get back the original equation.

$$H^{AR}_{Abs} - H^{VR}_{\Delta} = H^{AR}_{BL} \tag{24}$$

The purpose of all these mathematical jugglery was to show that, when we use the equation Eq. (24) given above, we assume that the gradient between the variometer and absolute room is a constant as given by (JL Rasson) [23] ie., dF is a constant. But we do not have any guarantee that this F gradient remains a constant in all the observatories. As already shown in Eq. (16), any variability in this gradient will get reflected in the baseline and makes it unstable. So we measure the variation in dF and use the extra error correction term involving dF for arriving at consistent baseline values using the modified equation. ie.,

$$H^{AR}_{Abs} - H^{VR}_{\Delta} - dF_{Var}Cos(I) = H^{AR}_{BL} \tag{25}$$

Following the same steps above, we can derive for the error correction term for Z component also and we get

$$Z^{AR}_{Abs} - Z^{VR}_{\Delta} - dF_{Var}Sin(I) = Z^{AR}_{BL} \tag{26}$$

We would like to emphasize the fact that, in deriving the equations above, we have not deleted or added or approximated any terms in the equations to arrive at the modified equation which means that the error correction term has evolved naturally without any artificial manipulations.

Because of the involvement of I term in both the above equations, it is only natural that the gradient drift error will manifest more in H baseline and the least in Z baseline in magnetic observatories nearer to the dip equator. Likewise the gradient drift error will be more pronounced in Z baseline and less in H baseline in high latitudes.

In the above derivation, we have taken into consideration only the drifting in F and we deliberately did not take the spatial variation of I into consideration. This was done intentionally to keep the derivation simple. But we know that every magnetic component has its own pattern of spatial variation. This is true for inclination also. So let us take into consideration the spatial variation of I also and retrace the above derivation.

3.4. Drift correction factor with dI included

$$H_{Abs}^{VR} - H_{\Delta}^{VR} = H_{BL}^{VR} \tag{27}$$

$$F_{Abs}^{VR} Cos\left(I_{Abs}^{VR}\right) - F_{\Delta}^{VR} Cos\left(I_{Abs}^{VR}\right) = F_{BL}^{VR} Cos\left(I_{Abs}^{VR}\right) \tag{28}$$

As earlier, let us say dF and dI are the difference in F and I between the variometer pillar and the absolute pillar, i.e.,

$$F_{Abs}^{AR} - dF = F_{Abs}^{VR} \quad and \quad I_{Abs}^{AR} - dI = I_{Abs}^{VR} \tag{29}$$

Substituting this in Eq. (28), we get

$$\left[F_{Abs}^{AR} - dF\right] Cos\left(I_{Abs}^{AR} - dI\right) - F_{\Delta}^{VR} Cos\left(I_{Abs}^{AR} - dI\right) = F_{BL}^{VR} Cos\left(I_{Abs}^{AR} - dI\right) \tag{30}$$

$$F_{Abs}^{AR} Cos\left(I_{Abs}^{AR} - dI\right) - F_{\Delta}^{VR} Cos\left(I_{Abs}^{AR} - dI\right) = F_{BL}^{VR} Cos\left(I_{Abs}^{AR} - dI\right) + dF Cos\left(I_{Abs}^{AR} - dI\right) \tag{31}$$

Expanding each terms in the above equation, the first term becomes,

$$F_{Abs}^{AR} Cos(I_{Abs}^{AR} - dI) = F_{Abs}^{AR}\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) = H_{Abs}^{AR} Cos(dI) + Z_{Abs}^{AR} Sin(dI) \tag{32}$$

the second term,

$$F_{\Delta}^{VR} Cos(I_{Abs}^{AR} - dI) = F_{\Delta}^{VR}\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) = H_{\Delta}^{VR} Cos(dI) + Z_{\Delta}^{VR} Sin(dI) \tag{33}$$

the third term

$$F_{BL}^{VR} Cos(I_{Abs}^{AR} - dI) = F_{BL}^{VR}\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) = H_{BL}^{VR} Cos(dI) + Z_{BL}^{VR} Sin(dI) \tag{34}$$

and the fourth term,

$$dF Cos(I_{Abs}^{AR} - dI) = dF\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) \tag{35}$$

The reduction

$$F_{\Delta}^{VR} Cos(I_{Abs}^{AR}) = H_{\Delta}^{VR} \tag{36}$$

and

$$F_{BL}^{VR} Cos(I_{Abs}^{AR}) = H_{BL}^{VR} \tag{37}$$

in Eqs. (33) and (34) is justified considering the fact

$$H_{Abs}^{AR} = F_{Abs}^{AR} Cos\left(I_{Abs}^{AR}\right) \tag{38}$$

can be expanded as

$$\left(F_{\Delta}^{VR} + F_{BL}^{VR}\right) Cos\left(I_{Abs}^{AR}\right) \tag{39}$$

which gets reduced to

$$H_{\Delta}^{VR} + H_{BL}^{VR} \tag{40}$$

Now substituting Eqs. (32)–(35) in Eq. (31), we get,

$$H_{Abs}^{AR} Cos(dI) + Z_{Abs}^{AR} Sin(dI) - H_{\Delta}^{VR} Cos(dI) - Z_{\Delta}^{VR} Sin(dI) = H_{BL}^{VR} Cos(dI) + Z_{BL}^{VR} Sin(dI) + dF\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) \tag{41}$$

splitting dF into $dF_{constant}$ and $dF_{variation}$,

$$= H_{BL}^{VR} Cos(dI) + Z_{BL}^{VR} Sin(dI) + (dF_{Cons} + dF_{Var})\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) \tag{42}$$

$$= H_{BL}^{VR} Cos(dI) + Z_{BL}^{VR} Sin(dI) + dF_{Const}\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) + dF_{Var}\left(Cos(I_{Abs}^{AR})Cos(dI) + Sin(I_{Abs}^{AR})Sin(dI)\right) \tag{43}$$

Dividing throughout with $Cos(dI)$ and moving second and fourth term in LHS to RHS,

$$H_{Abs}^{AR} - H_{\Delta}^{VR} = H_{BL}^{VR} + Z_{BL}^{VR} tan(dI) + dF_{Const}\left(Cos(I_{Abs}^{AR}) + Sin(I_{Abs}^{AR}) tan(dI)\right) + dF_{Var}\left(Cos(I_{Abs}^{AR}) + Sin(I_{Abs}^{AR}) \tan(dI)\right) - Z_{Abs}^{AR} tan(dI) + Z_{\Delta}^{VR} tan(dI) \tag{44}$$

since

$$dF_{Const} Cos(I_{Abs}^{AR}) = dH_{Const} \ and \ H_{BL}^{VR} + dH_{Const} = H_{BL}^{AR} \tag{45}$$

likewise for Z,

$$dF_{Const} Sin(I_{Abs}^{AR}) = dZ_{Const} \ and \ Z_{BL}^{VR} + dZ_{Const} = Z_{BL}^{AR} \tag{46}$$

Using the above relation in Eq. (44), we get

$$H_{Abs}^{AR} - H_{\Delta}^{VR} = H_{BL}^{AR} + Z_{BL}^{AR} tan(dI) + dF_{Var}\left(Cos(I_{Abs}^{AR}) + Sin(I_{Abs}^{AR}) \tan(dI)\right) - \left(Z_{Abs}^{AR} tan(dI) - Z_{\Delta}^{VR} tan(dI)\right) \tag{47}$$

Since $Z_{Abs}^{AR} tan(dI) - Z_{\Delta}^{VR} tan(dI) = Z_{BL}^{AR} tan(dI)$ the second, fifth and sixth terms on RHS cancels and we are left with

$$H_{Abs}^{AR} - H_{\Delta}^{VR} - dF_{Var}\left(Cos(I_{Abs}^{AR}) + Sin(I_{Abs}^{AR}) \tan(dI)\right) = H_{BL}^{AR} \tag{48}$$

So the drift correction term $-dF_{Var}Cos(I)$ for H component, with the inclusion of dI term gets modified into

$$-dF_{Var} Cos(I)(1 + tan(I) \tan(dI)) \tag{49}$$

with $(1 + tan(I) \tan(dI))$ as the extra term.

In the same manner the drift correction term $-dF_{Var}Sin(I)$ for Z component, with the inclusion of dI term gets modified into

$$-dF_{Var} Sin(I)(1 + Cot(I) \tan(dI)) \tag{50}$$

So Eq. (25) gets modified into

$$H_{Abs}^{AR} - H_{\Delta}^{VR} - dF_{Var} Cos(I)(1 + tan(I) \tan(dI)) = H_{BL}^{AR} \tag{51}$$

and following the same steps above, we can derive the error correction term for Z component also and Eq. (26) gets modified into

$$Z_{Abs}^{AR} - Z_{\Delta}^{VR} - dF_{Var}Sin(I)(1 + Cot(I)\tan(dI)) = Z_{BL}^{AR} \quad (52)$$

3.5. Experimental evidence of gradient drift

The main focus of discussion in this paper is about the error component involved in magnetic observatory data due to the variation in the difference between absolute room F and variometer room F. It was felt an experiment should be conducted to check and ascertain whether there was a gradient change in the F value recorded at variometer room and the absolute room. For a short period of time, an Overhausser GSM-90 was available for installation in the absolute room of Alibag observatory for conducting the experiment. The two overhausser PPM GSM 90 was run simultaneously at Absolute room and variometer from 17th October 2014 to 31st October. By operating the same model and make instrument at the variometer and Absolute room, we could ensure that there was no error involved in using two magnetometers of different make. Alibag observatory was chosen for conducting the experiment because of its magnetically clean environment without any artificial disturbances, where all types of magnetic calibration and compass corrections are carried out. The plot of dF (F Absolute room minus F variometer room) is shown in Fig. 6(a) for the period mentioned above. The plot clearly shows a drift of around 1.5 nT for a period of two weeks and shows smooth diurnal variations for certain days. There was a data gap from 24th October to 25th October due to instrument failure. The magnetic variation components delta D, delta Z and delta H are also shown in Fig. 6(a–c) for the corresponding period. The variation in dF does not correlate with the magnetic field component H, D and Z as inferred from Fig. 6. Possible reasons for this variations are detailed in the next section.

4. Results and discussions

We have applied these corrections to the Pondicherry H baselines and the results are shown in Fig. 7. Here we see a remarkable increase in the quality of the baseline. The total baseline drift for the period of 5 years is less than 2 nT.

The scatter plot Fig. 8 shows the dependency of the *H* baseline on *dF* before (grey) and after the correction (black). It is clear from the plot that after applying the correction, the dependency of the baseline on *dF* has reduced to zero.

In the earlier sections we have found that baseline drift can be caused by variation in *F* gradient and we derived an error correction factor which depends on *dF* and thus laid to rest the causative factor for one of the baseline instability. That is the term $e_{dF_{Drift}}(t)$ in

$$H_{Abs} - \Delta H = H_{BL} + e_{AbsH}(t) + e_{\Delta H}(t) + e_{dF_{Drift}}(t) \quad (53)$$

But the other two terms can still contribute to instabilities arising from measurement errors.

But it can be noted from Fig. 7, the correction term has eliminated not only the smooth drifting in the baseline but also the spreading. This is because of the fact when we measure dF_{Var} and apply the correction term, it does not differentiate whether the error variation in dF_{Var} is caused due to natural origin as described in the following section or due to the measurement errors. Because we have seen earlier that variometer itself has its own share of drifting error in addition to the spreading error. So the term

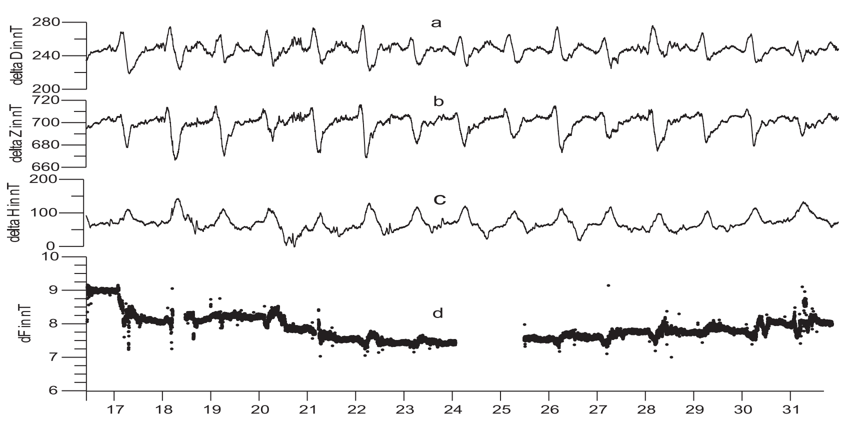

Fig. 6. The variation in magnetic field of D, Z and H respectively is shown in (a), (b) and (c). Variation in *dF* is shown in (d).

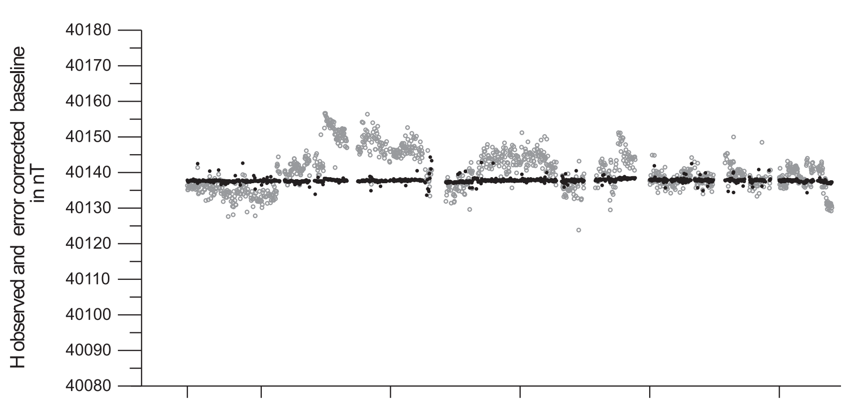

Fig. 7. Pondicherry H Baseline for a period of 5 years before applying the gradient drift correction (grey dots) and after applying the correction (black dots).

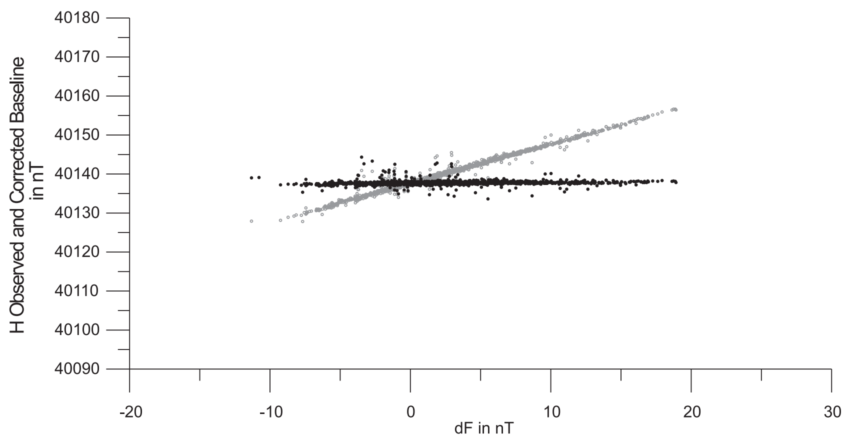

Fig. 8. Scatter plot shows the dependency of the *H* baseline on *dF* before (grey dots) and after the correction (black dots).

$dF_{Var}Cos(I)$ or the finer version of it $dF_{Var}Cos(I)(1 + tan(I)\tan(dI))$ takes into consideration the gradient drift as well as measurement errors and absorbs all the errors defined by $e_{AbsH}(t)$ and $e_{\Delta H}(t)$ to give a ideal H baseline. The same is true in the case of Z component also.

4.1. Reasons for gradient drift

The variation in gradient can happen due to many reasons depending upon the crustal structure of the locality, the soil chemistry of the observatory premises and even by the flow of ground water. Daniel Hellman [24] discusses about the current generated by the electrokinetic effect produced by the flow of groundwater. Toshiaki Mishima et al. [25] has found a correlation between the annual variations in the baselines caused by changes in soil magnetization in response to temperature changes. They found from their data the error in the baseline can go up to 7 nT/yr due to the changes in soil magnetization.

Andras Csontos [26] have found that baseline variation of Tihany observatory shows a good correlation with the water level of the nearby lake Kulso. They have found the presence of magnetite in the water of lake Kulso and the lake Belso. From these observations, they have concluded that the naturally magnetised water is able to modify the susceptibility of the area especially in the case of old variation house. Gawali et al. [27] discusses about the long term variations in the magnetic field generated due to peizomagnetic affects due to the stress build up in rocks.

5. Conclusions

We have shown earlier that theoretically a baseline has to be a straight line and the RHS of the fundamental equation Eq. (17) of an observatory should be a constant in the ideal case [7]. In theory, a baseline has to be a horizontal straight line.

We have further shown that baseline instabilities are caused by three factors. They are (i) measurement errors from absolute observations, (ii) measurement errors from variometer recording and from (iii) variation in gradient field between the absolute and variometer pillars. This variation in the gradient field causes long term drifts in baselines. As we have seen that drifting is the main factor which contaminates the purity of the data of an observatory, we have derived a drift correction factor. In the first attempt we derived the correction factor which takes into account only the variation in the difference between $F_{Absolute}$ and $F_{Variometer}$ and the drift correction factor is $-dF_{Var}Cos(I)$ for H component and $-dF_{Var}Sin(I)$ for Z component.

We included the spatial difference in I component also in the derivation and got a finer drift correction factor

$$-dF_{Var}Cos(I)(1 + tan(I)\tan(dI)) \tag{54}$$

for H component and

$$-dF_{Var}Sin(I)(1 + Cot(I)\tan(dI)) \tag{55}$$

for Z component. These correction factor was applied in Pondicherry baseline and we found that there was a remarkable increase in the baseline quality.

The analysis of long term geomagnetic data series of a geomagnetic observatory is the only way to investigate secular variation in detail and can throw more light on the deep interiors of earth and for modelling the electrically conducting fluid motions in the earths core [28]. As the stability of baseline is the most important criterion for evaluating the data quality of a ground magnetic observatory, any increase in baseline stability have a direct bearing on the quality of the magnetic data recorded and thus helps us in better modelling of geodynamo and other long term phenomena.

Acknowledgement

The authors are thankful to D.S. Ramesh, Director, Indian Institute of Geomagnetism for granting permission to publish this paper and for his constant support and encouragement. We also thank Prof. Satyavir Singh, Chief Coordinator of Observatory and Data Analysis division, for giving support and encouragement for carrying out this work. The first and second authors wish to express their deep gratitude to Prof. G.K. Rangarajan who initiated them to the interesting field of magnetometry and for his valuable guidance. We also wish to thank the two unknown referees for providing valuable inputs for improving the quality of this paper.

References

[1] I. Mandic, E. Vujic, B. Heilig, I. Pelajic, D. Herak, Recent efforts toward the establishment of the Lonjsko polje geomagnetic observatory, Acta Geophys. 64 (5) (2016) 1311–1339.

[2] A.G. Good, History Of Instrumentation. Encyclopedia of Geomagnetism and Paleomagnetism, Springer, Netherlands, 2007, pp. 434–439.

[3] D. Budker, M. Romalis, Optical magnetometry, Nat. Phys. 3 (4) (2007) 227–234.

[4] E.B. Aleksandrov, Advances in quantum magnetometry for geomagnetic research, Phys.-Uspekhi 53 (5) (2010) 487–496.

[5] I. Hrvoic, L.R. Newitt, Instruments and Methodologies for Measurement of the Earth's Magnetic Field. Geomagnetic Observations and Models, Springer, Netherlands, 2011, pp. 105–126.

[6] Sable Island Observatory, World Observatories Series Monthly Geomagnetic Bulletin August, British Geological Survey, 2000.

[7] J.L. Rasson, A.S. Potapov, V.E. Korepanov, S.Y. Khomutov, V.M. Krasnov, J. Bitterly, Report on upgrade of NIS magnetic observatories by the INTAS infrastructure action CRENEGON, Earth Planets Space 58 (6) (2006) 717–722.

[8] A. Chulliat, S. Anisimov, The Borok INTERMAGNET magnetic observatory, Russ. J. Earth Sci 10 (2008) ES3003.
[9] D. Kerridge, Magnetic observatories in the 21st Century: an endangered species?, Publ Inst. Geophys., Polish Acad. Sci. 100 (398) (2007) 299–307.
[10] A. Peltier, A. Chulliat, On the feasibility of promptly producing quasi-definitive magnetic observatory data, Earth Planets Space 62 (2) (2010) e5–e8.
[11] S. Macmillan, N. Olsen, Observatory data and the Swarm mission, Earth Planets Space 65 (11) (2013) 1355–1362.
[12] E. Clarke, O. Baillie, S.J. Reay, C.W. Turbitt, A method for the near real-time production of quasi-definitive magnetic observatory data, Earth Planets Space 65 (11) (2013) 1363–1374.
[13] J.L. Rasson, H. Toh, D. Yang, The Global Geomagnetic Observatory Network. Geomagnetic Observations and Models, Springer, Netherlands, 2011, pp. 1–25.
[14] X. Changjiang, S. Zhang, The analysis of baselines for different fluxgate theodolites of geomagnetic observatories, Data Sci. J. 10 (2011), pp. IAGA159-68.
[15] S. Zhang, D. Yang, Study on the stability and accuracy of baseline values measured during the calibrating time intervals, Data Sci. J. 10 (2011), pp. IAGA19-24.
[16] G.R. Small, Fluctuations in the H-Baseline value at Toolangi observatory, Bureau Mineral Resource Geol. Geophys. (1965).
[17] O. Rasmussen, E.K. Lauridsen, Improving baseline drift in fluxgate magnetometers caused by foundation movements, using band suspended fluxgate sensors, Phys. Earth Planetary Interiors 59 (1) (1990) 78–81.
[18] H.J. Linthe, J. Reda, A. Isac, J. Matzka, C.W. Turbitt, Observatory Data Quality Control-the instrument to ensure valuable research, in: Proceedings of the XVth IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition, and Processing. No. 03/13, 2013, pp. 173–177.
[19] A.D. Chave, A.G. Jones, The Magnetotelluric Method: Theory and Practice, Cambridge University Press, 2012.
[20] G.M. Turner, J.L. Rasson, C.V. Reeves, Observation and measurement techniques, Treatise Geophys. 5 (2007) 33–75.
[21] J. Matzka, A. Chulliat, M. Mandea, Geomagnetic observations for main field studies: from ground to space, Space Sci. Rev. 155 (1–4) (2010) 29–64.
[22] J. Jankowski, C. Sucksdorff, Guide for magnetic measurements and Observatory Practice. (1996).
[23] J.L. Rasson, About Absolute Geomagnetic Measurements in the Observatory and In the Field, Institut Royal Météorologique de Belgique, 2005.
[24] D.S. Helman, Earth electricity: a review of mechanisms which cause telluric currents in the lithosphere, Ann. Geophys. 56 (5) (2014) G0564.
[25] T. Mishima, T. Owada, T. Moriyama, N. Ishida, K. Takahashi, S. Nagamachi, Y. Yoshitake, Y. Minamoto, F. Muromatsu, S. Toyodome, Relevance of magnetic properties of soil in the magnetic observatories to geomagnetic observation, Earth Planets Space 65 (4) (2013) 337–342.
[26] A. Csontos, Long term baseline instability caused by an external influence, XVI IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, October 7–16, 2014.
[27] P.B. Gawali, S.Y. Waghmare, L. Carlo, A.G. Patil, Geomagnetic secular variation anomalies investigated through tectonomagnetic monitoring in the seismoactive zone of the Narmada-Son Lineament, Central India, J. Ind. Geophys. Union 15 (2) (2011) 61–76.
[28] S.S. Harlan, The earth's magnetism: an introduction for geologists, Eos, Trans. Am. Geophys. Union 88 (10) (2007) 123–124.