De-noising Diurnal Variation Data in Geomagnetic Field Modelling

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Abstract Ground based geomagnetic observatory series have been used to investigate and describe the residuals between a continuous geomagnetic field model and observed diurnal variation for noise-removal of signal due to external field of magnetospheric ring current sources. In all the observatories studied, the residuals in the X-direction consistently show the noisiest signal. Results show that the residuals in the X-direction correlates closely with the RC-index, suggesting an origin from unmodelled external field variation. Notable cross-correlation is also seen between the residuals and the RC-index at zero-lag. Removal/reduction of this unmodelled signal enhances resolution of fine-scale detail in diurnal variation studies.

Key words: External field, Ring Current, RC-index, Geomagnetic observatories, eigendirections, noise/signal.

1. Introduction

The diurnal variations in the external geomagnetic field is a powerful source for the understanding of certain structure and processes in the deep Earth study. Geomagnetic diurnal variation study is of great interest in geomagnetic field modelling. The quiet-time diurnal variation modelling, particularly the separation of the dominant external field sources, the ionospheric and magnetospheric signals, allow improved geomagnetic sounding of the upper mantle electrical conductivity (Constable and Constable 2004) and are key elements for measurements, studying and understanding of induction effects and conductivity structures within the Earth (Mareschal 1966; Banks 1969; Schultz and Larsen 1990; Constable 1993; Olsen 1999; Kelbert et al. 2009; Khan et al. 2011). Ionospheric signals as measured by geomagnetic ground observatories, particularly in equatorial and auroral regions, represent the largest source of uncertainty in current global field modelling. To better constraint these signals is crucial for progress in many areas of geomagnetic field study. Interpretation of external variation field signals is hampered by rapid changes in the electrical current systems of the magnetosphere and ionosphere and these signals induce secondary magnetic fields in the deep Earth indistinguishable from main field variations. This has made it imperative for proper treatment of the effects of diurnal field variations for appropriate study of main field variations.

Two types of variations are typically revealed when continuous measurements of any of the components of the geomagnetic field is examined:

- Measurements of non-polar latitudes usually display a smooth regular variation, known as the solar quiet diurnal or Sq variation, which originates as the magnetic signature of E-region ionospheric currents that is driven by dynamo action (Campbell 1989; Richmond 1995a; Richmond and Maute 2014).
- Measurements sometimes display rapid irregular fluctuation ('wiggles') referred to as geomagnetic disturbances (in different level of magnitude), the disturbances may be such that the regular diurnal Sq (quiet-time) variation is overwhelmed and is not easily observable. Even though the Sq variation is the most regular of all the geomagnetic field variations (as a result of its 24-hour periodicity), it shows significant day-to-day variability (Okeke et al. 1998; Bhardwaj et al. 2015).

At ground geomagnetic observatories, external field variations can be adduced, to some extent, to average out over time, unlike with satellite measurements which do not, as it is rare for satellites to return to precisely the same point. Modelling can best be attempted by fitting a global model for quiet time data, with various aspects of the external field parameterized in terms of Dst-index, or better still the new RC-index. Ground geomagnetic observatory measurements provide excellent temporal coverage. Because measurements are taken at a single location averaging over time i.e. minutes, days, weeks, months or years, can minimise greatly any zero mean noise. But since the coverage of geomagnetic observatories is far from uniform all over the globe, and as the geomagnetic field contains a strong component of the short-wave crustal field and induced time-varying field of external origin, this potentially means they still contain an amount of noise (particularly as we move away from quiet time measurements).

Numerous approaches have been shown in geomagnetic field modelling to account for external field variations. Two major approaches can be distinguished. Firstly, the variations, both internal and external, can be parameterized and modelled and the various contribution co-estimated at all length and timescales. Secondly, the variations can be treated stochastically as data errors in a simple inversion for main field only (Bloxham and Jackson 1992; Jackson et al. 2000). However, the two approaches have been combined in some recent models (Olsen et al. 2009). The comprehensive approach (using the comprehensive model) of Sabaka et al. (2002, 2004), where the internal and external field sources are parameterized and co-estimated, is the most detailed attempt to model the sources, and solve for magnetically quiet external field variations and the signals they induced, modulated by geomagnetic activity indices, such as Dst and F10.7.

In this paper, we chose the comprehensive approach and attempt to use the Comprehensive model, CM4, (which uses both satellite and observatory measurements) to provide the most information about the field. We modelled the external and treat residuals of the field sources comprehensively. The main data and estimates of the external field variations were provided by the CM4 and geomagnetic observatory measurements, which we assumed to have a constant variance over the modelling interval. But we allowed for allowance for covariance between the errors on the three vector field components at any one location. We made use of all the data processing and expertise used in the comprehensive model, considering the residuals (i.e. noise), and specifically seeking unmodelled signals and present a correlation analysis for the observatory data and the first differences of the RC index, showing the case that the largest error is associated with the X-direction variation. We also examined the variation in the three directions, after correcting for the noise in the signals.

2. Data

Here in this section, we present the data employed in carrying out this study. The data used in this work are magnetic observatory minutes and hourly means measurements. The data used are based on measurements taken from a network of geomagnetic observatories in Africa. We have more than these number of geomagnetic observatories in Africa, but only used those that reported definitive measurements during the period under study. We employed moderately disturbed (Kp ≤ 5) minutes and hourly means measurements, where available, at each observatory studied. For more complete description of observatory data and the various signals they accommodate, we refer the reader to Matzka et al (2010), Reason et al (2010) and Love and Chulliat (2013). These data were obtained from minutes and hourly values downloaded from the Intermagnet database (available at http://www.intermagnet.org). Where such data were unavailable, we used minutes and hourly means provided by the World Data Centre for Geomagnetism, Edinburgh (available at http://www.wdc.bgs.ac.uk). Although the coverage and regular occupation of geomagnetic observatories across Africa mainland are sparse compared to other parts of the globe, particularly Europe, this study is only meant to give an insight or explore idea into the background diurnal variation and their signals.

For field modelling in this study, the three components of the geomagnetic field, X (northward), Y (eastward) and Z (downward) were compiled for each of the African observatories where measurements are taken. The measurements were also corrected for baseline jumps, were previously reported. All the observatories used throughout this study are shown in figure 1, and listed in table 1, together with their codes and position (latitudes and longitudes).

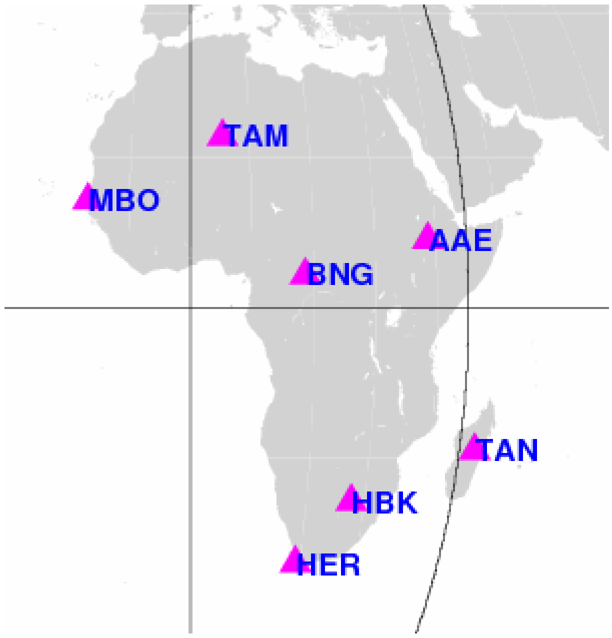

Figure 1: Location of the geomagnetic observatories in Africa were measurements used in this study were taken.

Table 1: List of observatories used throughout this study, together with their code and position (latitude and longitude).

Observatory	Code	Latitude	Longitude
Addis Ababa	AAE	9.03	38.77
Antananarivo	TAN	-18.92	47.55
Bangui	BNG	4.33	18.57
Hartebeesthoek	HBK	-25.88	27.71
Hermanus	HER	-34.43	19.23
Mbour	MBO	14.38	343.03
Tamanrasset	TAM	22.79	5.53

3. Modelling Methodology

Here, we summarised the modelling procedure used in this study. We considered the hybrid approach in the modelling procedure, using the comprehensive modelling and the stochastic (covariant) modelling approach.

3.1. The Comprehensive Approach

The comprehensive approach entails using the comprehensive magnetic field model (CM4) of Sabaka et al (2004), derived from geomagnetic ground observatory data as well as from different geomagnetic satellite mission measurements. Some of the contributions to the geomagnetic field, in terms of the spatial and temporal scales, overlap. This makes it complicated separating their various effects from samples of the observed field. To overcome this, the comprehensive modelling was developed, with the CM4 as one of the models, which has proved to be very successful. The CM4 shows great improvement in terms of the time span, completeness of sources, and noise reduction in the recovered parameters. The CM4 also show great advancement in separating the main (internal) field from the external field signals, and even the associated induced signals from the internal, during quiet-time periods. It has also provided a global description of the field's evolution through time.

We reasoned that the CM4 would be particularly useful in the study of the geomagnetic diurnal variations in the African area, where there is sparseness in geomagnetic observatories. It is interesting to investigate the geomagnetic diurnal variation effects with time scales of few minutes to a few days with the corrupting effects of high geomagnetic variations due to unmodelled signals from intense external field current systems that occur in the ionospheric and magnetospheric source regions. The comprehensive modelling approach can assist in the study of the diurnal variations, especially away from quiet-time where the external interferences are quite high.

Assuming the CM4 parameterizes and separates the different contributions to the geomagnetic field properly, the comprehensive modelling approach allows us to secure diurnal variation signals free from internal filed influences and its secular variation effects, as well as the spatial biases of improper geomagnetic observatory distribution. Available observatory hourly means for the different geomagnetic field components X, Y, and Z are compared with synthetic means determined from CM4 for each observatory location. CM4 also allows us to determine the local X, Y, and Z geomagnetic field components relative only to the diurnal variation field post-2002.5, after the extension we performed on the CM4 original timespan (for more on this CM4 extension, see Onovughe and Holme, 2015).

3.2. Covariant Modelling Approach

The data error was carefully considered, knowing that the complex signature from the external fields contributes significantly to the data error and so attempt a sequential elimination of the sources. Accurate magnitude of the data error covariance is required in order to provide realistic a posteriori confidence levels. In previous studies for the main field, Wardinski and Holme (2006, 2011) and Wardinski and Lesur (2012) using principal component analysis, found large connections between the residuals from a main field model and the Dst magnetic index. They went on to remove from the data a statistical proxy for unmodelled signals of external origin. This may look promising in study for secular variations patterns of observations. Studies have shown that indices such as Dst do not necessarily represent well the external activity worldwide (particularly, outside quiet-time), and biased at certain periods due to time changes of Dst baseline (Olsen et al. 2005b; Luhr and Maus 2010; Onovughe and Holme 2015), as a result we went for the alternative RC index which has been recently developed and works well for external field variations (Olsen 2002; Thomson and Lesur 2007; Olsen et al. 2014).

Ideally, in spherical harmonic modelling of this nature, the comprehensive approach may be recommended, where all signal sources are simultaneously accounted for in order to allow for unmodelled signals to disappear as much as possible, however, this is not possible when dealing with external field measurements, and particularly for days of high magnetic activity (i.e. days away from quiet-time). In this instance, modelling errors have to be contemplated along with the uncertainties in measurements.

In this study, we have gone ahead to model the geomagnetic data, after using the comprehensive model to parameterize the observatory data. By seeking a continuously time varying field model from an iterative least-squares fit to the data we minimize

$$e^T C_e^{-1} e \quad (1)$$

where e is the vector of the errors i.e. the residuals between the model and observation, and the data error covariance matrix

$$(C_e)_{ij} = \mathbf{cov}(e_i, e_j) \quad (2)$$

Is diagonal (covariance = 0 $i \neq j$) if the errors are assumed to be uncorrelated.

To consider all error correlations in space and time would require the inversion of a dense matrix at great computational cost; as a result, we examined the correlation of data errors and constructed a 3 x 3 error covariance matrices within each location. The covariance matrix is then block diagonal with 3 x 3 blocks for each site, which could easily be inverted. Following Holme and Bloxham (1996), each subblock of the data error covariance matrix can be stated as a sum of vector dyadic, if the eigenvectors, v and eigenvalues, λ are known

$$\mathbf{C_e} = \sum_{i=1}^{3} \lambda_i V_i V_i^T, \quad \mathbf{C_e^{-1}} = \sum_{i=1}^{3} \frac{1}{\lambda_i} V_i V_i^T. \quad (3)$$

Noting that the eigenvalues of a real symmetric matrix are real and its eigenvectors are orthogonal. Each eigenvalues and eigenvectors were computed iteratively from the covariance matrix of the residuals at each observatory location.

The final eigenvalues, λ and eigenvectors, v for Addis Ababa (AAE) is shown, as an example.

λ_1 = 396.73nT/hr; v_1 = 0.974, 0.210, 0.081
λ_2 = 79.78nT/hr; v_2 = -0.209, 0.978, -0.025
λ_3 = 32.73nT/hr; v_3 = -0.085, 0.007, 0.996

with the eigenvectors, v_i having three components in the local Cartesian frame, the X, Y, and Z direction. The application of correlation between the three vector components at a particular location was first considered in the modelling of attitude error in vector magnetic satellite data (Holme and Bloxham 1996).

The result of the eigenvalues and eigenvectors in each components of the variation obtained from the observatory data at each location show that the X-direction is consistently the noisiest (most disturbed), with the Z-direction the least disturbed. The eigenvalue is an indication of the noise level in the variation, and the eigenvector directions are controlled by the noise in the data (Wardinski and Holme 2011). The Z-direction, the smallest eigenvalue, has the lowest contribution from unmodelled external noise and the X-direction is the most disturbed.

Our observation shows that the X-direction is aligned approximately north-south consistent with the expected result that the error is dominated by large-scale unmodelled external field signature of the ring current. The Z-direction has much lower noise than either the X- and Y-directions. The external and corresponding induced field are primarily contained in the noisy direction and has much influence on the field modelling. The consideration of error covariance enabled us to fit the data more closely with reduced risk of external field contamination which is always there in abundance, allowing us to take advantage of higher resolution of temporal basis. Figure 2 shows the observed and modelled diurnal variation estimated into the three eigenvector directions for four observatories, Addis Ababa (AAE), Bangui (BNG), Hermanus (HER) and Tamanrasset (TAM).

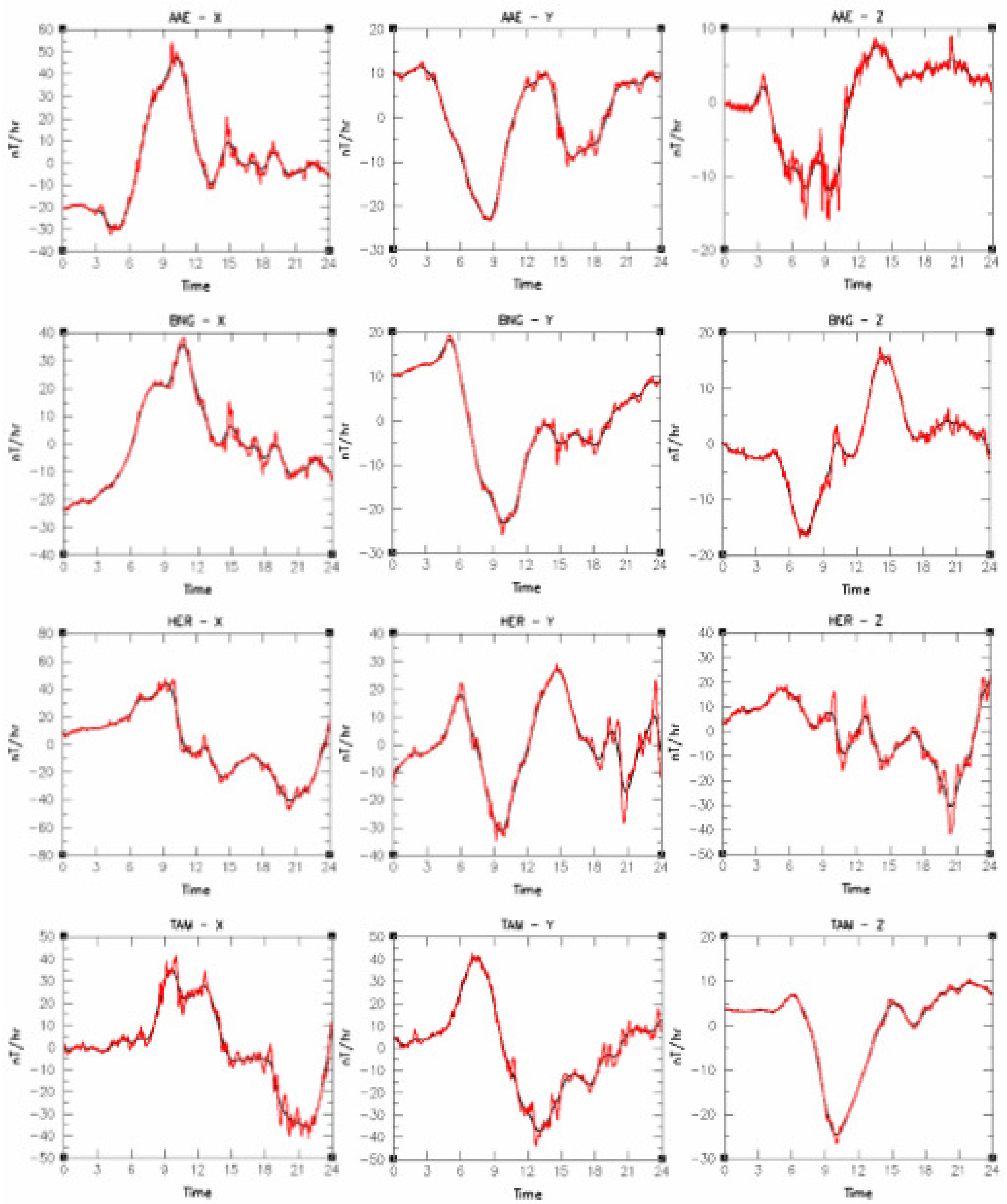

Figure 2: Modelled diurnal variation (red line) and the diurnal variation estimates (black line) in the three eigendirections (X-, Y- and Z-directions) at some selected African geomagnetic observatories (AAE, BNG, HER and TAM).

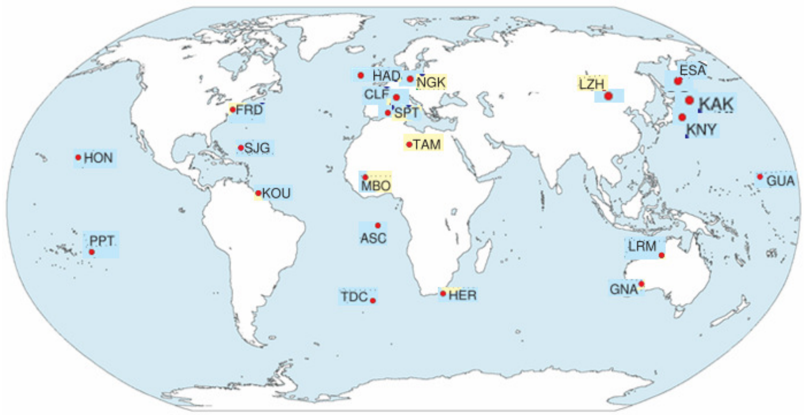

Figure 3: Location of the geomagnetic observatories used in calculating the RC-index measurements. TAM, MBO and HER are African observatories used in this study.

4. Modelled Residuals and Correlation with External Field Variation

Theoretically speaking, we assumed that the errors contained in the data are strongly influenced by signals from large-scale magnetospheric ring current. This is not surprising as the data are diurnal variation data of largely external field origin. Here we performed a correlation study between the residuals of our hourly mean measurements and that of the RC-index in the three eigendirections.

4.1. The RC-index

Conventionally, the time-space structure of the external field variations (particularly the magnetospheric field) is described using the Dst-index in geomagnetic field modelling (Suguira 1964); Olsen et al 2014). However, Dst measures only the axially symmetric ring current, and the baseline of Dst is known to change with time, which hampers its use in geomagnetic field modelling (Olsen et al.2005; Luhr and Maus 2010). Dst-index also contains contributions unrelated to magnetic storms such as seasonal variation of the quiet-time level (Cliver et al. 2001). In an attempt to overcome these difficulties associated with Dst, and improve the parameterization and time dependence of the ring current, data from geomagnetic observatories distributed worldwide (unlike Dst that is limited in terms of distribution of contributing observatories – only four) were used to derive a modified new index, called RC. RC is derived by an hour-by-hour spherical harmonic analysis (SHA) of hourly mean values from 21 observatories at mid and low latitudes (see figure 3). It describes the strength of the magnetospheric ring current even during geomagnetic quiet periods, normally when the baseline instabilities of Dst-index lead to less-optimal outcomes. Using the RC-index instead of the Dst-index improves the fit to data considerably.

In this study, a significant concern is the outstanding unmodelled diurnal variation signals relating to Dst in the RC-index. Not described in detail by Olsen et al (2014), we assumed that these variations relating to Dst were removed when they computed the RC-index, thus improving RC-index fit to the diurnal variation data. Additionally, in using the RC-index in this study, we take RC and remove a trend from Dst (in other words, looking at small temporal scale ring current variation after the subtraction of Dst). This is to de-noise the signal and remove any unmodelled diurnal variations.

4.2. Correlation between Residuals (Observatory Data and RC-index)

We looked at the correlation between the residuals in the three eigendirections and that of the RC-index. This was estimated by using the cross-correlation function, defined according to Wardinski and Holme (2011),

$$R_{(l)} = \frac{\frac{1}{(N-l)}\sum_{k=1}^{N-l}\{[x(k)]\ .\ [y(k+l)-\dot{y}]\}}{\sigma_x .\ \sigma_y} \qquad (4)$$

This measures the mutual correlations between two independent series x, y (set as the eigendirections and the RC-index) with sampling length N at sample lag l. σ_x and σ_y represents the standard deviations of the series x and y, $\dot{x}$ and $\dot{y}$ denote the mean. To avoid so-called large-lag standard error, we adopted a maximum lag, l = 120, which is 1/11th of the total series length (Box and Jenkins 1990).

Here, we first show the correlation comparison between all three eigendirection residuals and the RC-index in figure 4 for some selected observatories (BNG, MBO and TAM). From the correlating comparison, the two curves (the RC-index and the X-direction residuals) match each other closely. Looking at the correlating signals, the correlation of the X-direction profile with RC-index is clear. This is not the case for the curves between the RC-index and the Y- and Z-direction residuals. We observe clear anti-correlation for most of the time between the curves. The correlation of the X-direction with RC-index suggests that this signal may be of external origin to the Earth or related to signals of magnetospheric ring current.

We then calculate the cross-correlation at zero lag (l = 0) for all three eigendirections with the RC-index. The zero-lag cross-correlation between the X-direction residuals ranges between 0.70 and 0.95, that of Y-direction 0.30 and 0.55, and Z-direction -0.35 and 0.50. The cross-correlation results show that the X-direction is always greater than the cross-correlations between the RC-index and the residuals of the other two directions (Y- and Z-directions). This clearly shows that large-scale ring current signature exists to a far greater magnitude in the X-direction (noisy direction) than in the other two directions. It is likely that simple correlation between the RC-index and the residuals of the different eigendirections is disrupted by signal from external current systems in the D and E regions of the ionosphere, particularly for the X-direction. The good correlation observed between the RC-index and the X-direction residuals (in figure 4) show the strong influence of the ring current on the diurnal variation residuals (i.e. the X-direction) at these African observatories, despite the additional 'noise' from unmodelled signals and external current systems. Results for the cross-correlation coefficients between the RC-index and three eigendirection residuals is presented in table 2. The strong cross-correlation between Mbour (MBO) and Tamanrasset (TAM) may not be overly surprising as these observatories are part of the observatories from which the RC-index is constructed. Only in Hermanus (HER), another RC-index observatory, where we see a slightly lesser cross-correlation coefficient with the RC-index than other non-RC-index observatories. This may be due to additional non-coherent, non-RC related signals present in the residuals.

Table 2: Zero-lag cross-correlations coefficients between the RC-index and the residuals in the X-, Y- and Z-directions for African observatories used in the study.

Observatory	**Code**	**RC Index vs X-direction**	**RC Index vs Y-direction**	**RC Index vs Z-direction**
Addis Ababa	AAE	0.80	0.45	0.25
Bangui	BNG	0.85	0.50	-0.35
Hartebeesthoek	HBK	0.75	0.30	0.20
Hermanus	HER	0.70	0.30	0.20
Mbour	MBO	0.95	0.55	0.50
Tamanrasset	TAM	0.95	0.50	0.40
Antananarivo	TAN	0.75	0.30	0.30

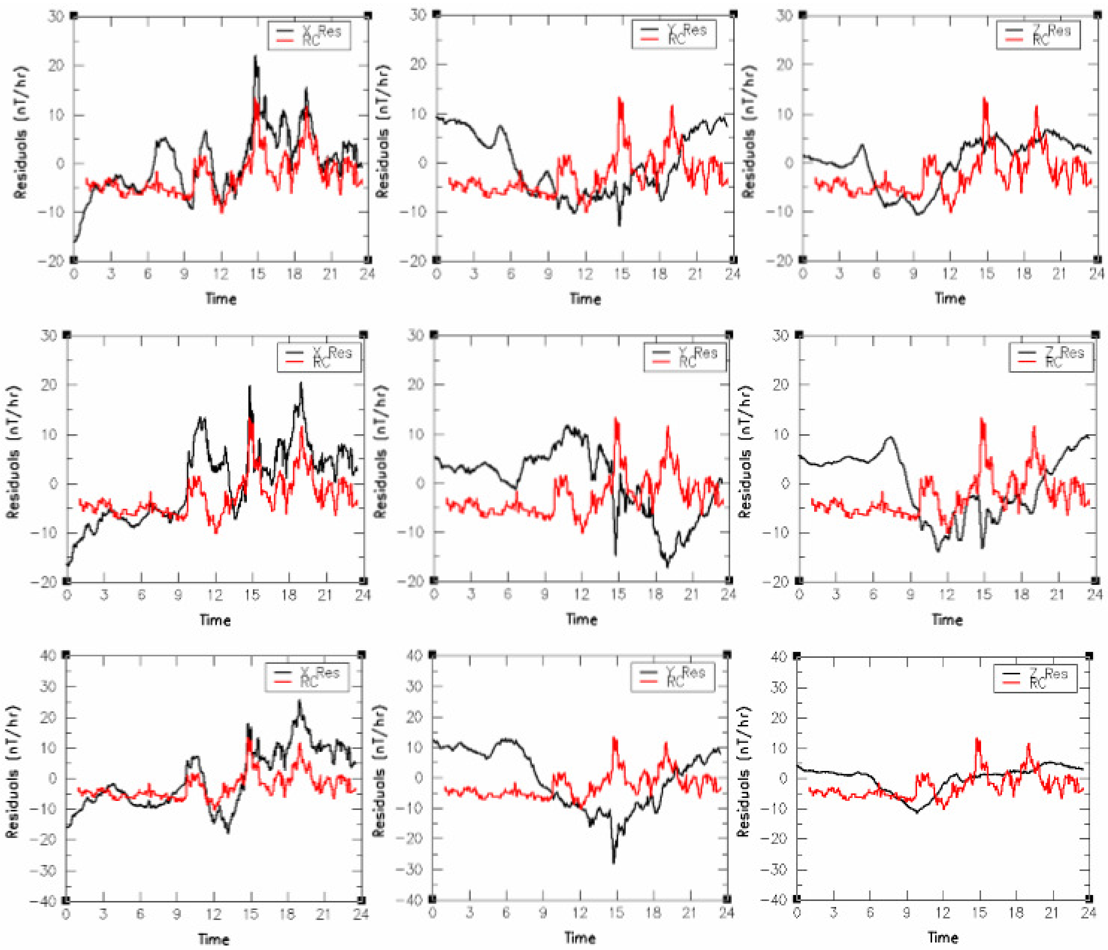

Figure 4: Correlation between the residuals in the three eigendirections and the RC-index, at three African observatory locations BNG, MBO and TAM from top to bottom. The correlation with X-direction is clear, while with the Y- and Z-directions we can see clear anti-correlation.

Table 3: Standard deviation of uncorrected magnetic diurnal variation field components and denoised diurnal magnetic field components (marked with *) at African observatory locations used in the study

Observatory	Code	X	X*	Y	Y*	Z	Z*
Addis Ababa	AAE	7.9	5.8	3.0	2.9	8.9	8.9
Bangui	BNG	5.8	4.1	3.4	3.3	7.4	7.3
Hartebeesthoek	HBK	5.5	4.6	4.2	4.1	3.4	3.3
Hermanus	HER	5.4	3.5	5.2	5.0	2.8	2.5
Mbour	MBO	4.9	2.0	2.2	2.1	4.8	4.7
Tamanrasset	TAM	3.8	2,0	1.8	1.6	3.1	3.0
Antananarivo	TAN	6.7	6.0	5.3	5.3	6.3	6.1

In summary, the X-direction at these African observatories studied, correlates clearly with the RC-index, but not so for the Y- and Z-directions. The strong correlation between the signals of the X-direction and the RC-index from different observatories leads us to suggest that local differences in the underlying crustal and mantle conductivity only minimally effects the residuals (in terms of outline of their time variation is concerned). In a different situation, we would expect the cross-correlation between the RC-index and the residuals to vary more markedly with location.

5. Removal of 'Noise'-related or Unmodelled Signal

Results from the section above gives us enough confidence to posit that the residuals in the X-direction include a substantial component related to unmodelled external field variation, arising from the magnetospheric ring current. As a result we decide to solve for a contribution to the X-direction residuals linearly related to the hourly means of the RC-index. Assuming a linear relationship

$$\{a_i\} = \times\{b_i\} \qquad (5)$$

where a_i and b_i are the residuals and hourly means of the RC-index at a time i and x the proportionality constant. The best fit to the data yields a RC-based convection to the residuals of

$$\hat{a}_i = a_i - \frac{\sum_{j=1}^{N} b_j a_j}{\sum_{j=1}^{N} b_j^2} \qquad (6)$$

The correction approach relates the model and the data into the eigendirections of the data error covariance matrix using equation 7 below, and the residuals are computed.

$$P_i(t) = Q(t).\mathrm{v}_i \quad \text{for } i = 1, 2, 3 \qquad (7)$$

where P_i are the three eigendirections, Q is the data vector composed of $\frac{dX}{dt}$, $\frac{dY}{dt}$, $\frac{dZ}{dt}$ and v_i are the eigenvectors of each observatory. The direction of the smallest eigenvalue, Z-direction, has the lowest contribution from external noise and the X-direction is the most disturbed as already alluded to above. The noise-improvement procedure outline in equation 6 is applied to residuals in the X-direction. This produces a diurnal variation sequence with lessen unmodelled external field signal. This is shown in figure 5, with the comparison between the corrected and uncorrected data in the X-direction showing clear improvement in most of the observatories, especially in times when the rapid fluctuation are larger in the diurnal variation.

This procedure was only applied to the residuals in the X-direction, because as shown, it is the component that is most affected by the unmodelled signal ('noise') of the external (magnetospheric ring current) sources. Also, the cross-correlation between RC-index and the residuals in the other two eigendirections (Y- and Z-directions) are too small to substantiate the formalism (see figure 4). To evaluate the noise-reduction, the standard deviation for the corrected and uncorrected data at each observatory is determined/quantified. This is summarise in table 3 above for all the observatories studied. Although, results show that the effects of noise-removal varies between observatory locations, however, a decrease is observed in every observatory, even observatories whose correlation coefficient is less than the others i.e. Hermanus (HER).

6. Conclusion

We present in this study a method developed by Wardinski and Holme (2011) to study and correct for noise in diurnal variation data due to unmodelled signals of external field variation associated with large-scale magnetospheric ring current. Although, their approach and study was applied to secular variation data, we used the same approach as the signal we intend to remove is of external field-related as that in their study.

In our study, we analysed ground observatory residuals from the comprehensive model (CM4) in the principal directions of the data error covariance matrix. We also performed correlation and cross correlation with daily first differences of the RC-index. In most of the observatories studied, the residuals in the X-direction consistently show the noisiest signals, and also show a clear zero-lag correlation with RC-index. We applied this procedure by Wardinski and Holme (2011) to use this correlation to reduce the contributions to the diurnal variation due to unmodelled external field variations. This was successful for most of our observatories, where the zero-lag cross correlation with the RC-index is large. This result clearly suggests investigating the progress of an RC-index proxy for modelling the external geomagnetic field – particularly using many observatories. This could also be used a posteriori to find anomalies and misfit in geomagnetic observatories, as better understanding of the error improves field modelling of diurnal variation data.

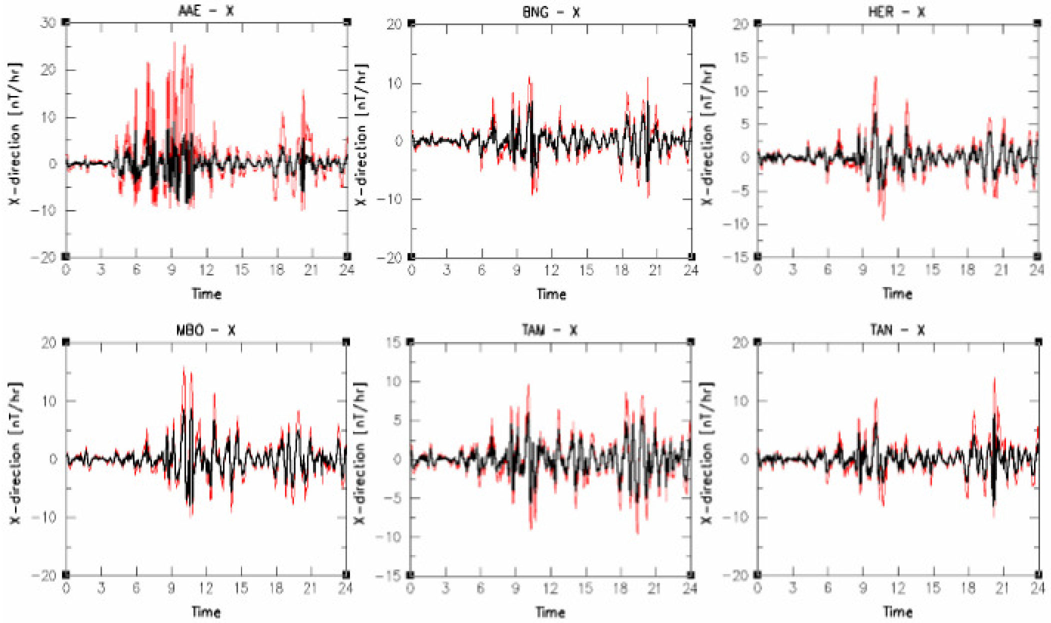

Figure 5: Comparison between the unmodelled i.e. uncorrected (red line) and denoised diurnal variation (black line)applied to the residuals of the X-direction in selected African observatories – Addis Ababa (AAE), Bangui (BNG), Hermanus (HER), Mbour (MBO), Tamanrasset (TAM) and Antananarivo (TAN).

While we have concentrated our study/analysis on noise-removal on the simple correlation between the RC-index and the X-direction residuals at zero-lag, there remain many attributes of interest still unexplained. For example, there may clearly contain information about inductions in the directions and magnitudes of the eigenvalues of the X-direction (noisy direction) which may not be easily explained by this formalism. Also, the influence of other indices, such as D_{st} and $F_{10.7}$ also require consideration. Progress in understanding and solving for the contributions to diurnal variation due to unmodelled external field variations can be achieved. Looking at non-zero lag correlations, using many more observatories from around the globe, particularly in high latitude/auroral regions and improved subtraction of D_{st}-related signals from RC-index would suffice. These are subject of ongoing study/research to be presented in the future.

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