Cross-Correlation Analysis of Geomagnetic Observatory Components, X, Y, Z and The Geomagnetic Index, RC in Geomagnetic Exploration Studies.

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Abstract

A cross-correlation study between the geomagnetic components (X, Y, Z) and the geomagnetic magnetospheric ring current activity (the RC index) is made for more than 80 worldwide geomagnetic observatories for days away from quiet time (disturbed days). Results suggest a strong relationship between the geomagnetic observatory measurements, particularly the X component, and the RC index. Strong coherence and correlation are observed between the X component and the RC index in all the observatory locations studied in all the geographical regions of the Earth. Cross-correlation coefficients ranged between 0.70 and 0.85 for the comparison, suggesting global phenomenon. However, the Y and Z components comparison with the RC index show low correlation and anti-correlation, with cross-correlation coefficients of between -0.55 and 0.50 in most of the observatory locations globally. This lack of clear correlation between the Y and Z components and the RC index suggests lack of influence of the external field variations, but consistent with the ring current influencing the rapid variations observed in the X components during disturbed days.

Keywords: Geomagnetic components, Cross-correlation, RC index, Disturbed days, Geomagnetic observatories

1.0 Introduction

Magnetic methods, particularly from ground based, marine-based and airborne (aeromagnetic) acquisition, are of significant importance in geophysical exploration, particularly to cover large areas of remote landscape. These methods are easy to apply, fast, and relatively low-cost. An essential phase in processing measurements from these magnetic surveys/explorations is remote referencing i.e. measurements from a fixed base station are subtracted from survey measurements to minimize contamination from rapidly-varying field sources. In remote referencing, surveys are referenced to a base station to remove time-varying effects from survey measurements. It is assumed that these time-varying effects occur concurrently at both the base station and the survey location (Nichols et al. 1988; Lilley et al. 1999). Also, that the base station and survey location are measuring similar variations in the external geomagnetic fields. These surveys are an important method of understanding subsurface geology, but there are several reasons why correction by remote referencing may not work or fail. These reasons include induced effects, activity levels of the field, and the distance between survey and the base station. Our focus in this study is the activity level of the fields.

The magnetic disturbance level of the geomagnetic field presents concern in surveying work, particularly for disturbed days. This is when the geomagnetic field variation is somewhat irregular. There exist various geomagnetic activity indices which have been designed to describe the irregular geomagnetic field variations (Verbanac et al. 2010). The various geomagnetic indices not only represent a good indicator of the magnetic field variations, they also give a global picture of the degree of disturbance level, thereby providing information about the complex underlying phenomena.

The Dst index is the geomagnetic index that is traditionally used to study the geomagnetic field during times of high geomagnetic activities i.e. magnetic storms, and the Earth's current system, in particular the development of the ring current (Karinen and Mursula 2006). The Dst index aim to monitor variations of the equatorial magnetospheric ring current, but it has been known to suffer setbacks when used in geomagnetic modelling, especially during times of rapid variations observed during disturbed days. This is because Dst baseline changes with time i.e. baseline instabilities, and time dependence (Olsen et al. 2005; Luhr and Maus 2010). In order to enhance time dependence and better describe the strength of the magnetospheric ring current during conditions when the Dst reports instabilities in baseline and give less than optimal results, the ring current (RC) index was built by Olsen (2002). Like the Dst index, the RC index also aim to monitor variations of the equatorial magnetospheric ring current. The RC index focusses on having a stable baseline and accounts for secular variations more consistently across observatories by removing a time-dependent core field model. For more on the Dst and RC indices see Sugiura (1969) and Olsen (2002).

Geomagnetic disturbed periods are due to higher levels of activity in the Sun, which is linked in large part to the 11-year sunspot cycle. Geomagnetic disturbed activities are associated with large changes in speed or density of the solar wind, often caused by solar flare events (Papaioannou et al. 2009; Badruddin 2002). The influx of these charged particles enhances the ring current, causing a decrease in the strength of the geomagnetic field at the equator. The decrease is mainly in the horizontal (X) component, measured by the Dst index. This is because the main phase of the disturbed activity is a large, rapid, decrease in X (i.e. increase in the strength of the ring current). Geomagnetic disturbed time activities often lead to loss of data from geomagnetic surveys, as measurements collected is rendered unusable by the effects of the disturbed time activities. Understanding the nature of the geomagnetic disturbed time activities i.e. as it relates to the large-scale magnetospheric activity and the geomagnetic components (X, Y, Z), is key to enhanced measurements preservation and corrections in geomagnetic exploration, particularly for days away from quiet time (disturbed days).

In this study, we performed a cross-correlation analysis between the geomagnetic ring current activity (RC) index and the geomagnetic components (X, Y, Z) for days away from geomagnetic quiet time. A total of more than 80 geomagnetic observatories scattered around the globe was studied. This is to show that the rapid variations observed in observatory component measurements is coming from a large-scale source, probably due to large scale magnetospheric ring current, and that the signals are fairly the same in most places on the Earth. Also, to show that the RC index is a good representation for rapid variation measurements for most observatories globally. Moreover, corrections of geomagnetic survey measurements acquired during disturbed time period may be considered global, particularly the diurnal variation components.

2.0 Data Used

In this paper, we apply the geomagnetic measurements collected during regular magnetic measurements of more than 80 worldwide INTERMAGNET network observatories. The list of representative observatories located at different geographical regions of the Earth which results are presented in this study is shown in table 1. The table shows the name of each observatory, IAGA code, geographical coordinates, institute, status in INTERMAGNET network, country of location and GINs (Geomagnetic Information Nodes). The basic measurements used are based on the observatory hourly means (OHMs) of the three geomagnetic observatory components i.e. the North (X), the East (Y), and the vertical downward (Z) components.

Since the main interest is study of the rapid variations in large scale magnetospheric activity, we have chosen measurements based on the diurnal variation (as they contain components of external fields contributions) for disturbed days. We made use of the Kp index to distinguish the quiet days from the disturbed days (Campbell, 1989; Joselyn, 1989), For the disturbed days we use $3 \leq Kp \geq 5$, and OHMs measurements at the selected geomagnetic observatories for the period between May and September 2006. All the measurements are diurnal variation measurements recorded within a 24-hour period for the selected disturbed days. The study takes into account the established fact that the diurnal variation field is largely a local time field that can be largely represented by a current fixed relative to the Sun (Price, 1969). As a result, we make use of the Universal Time (UT) to observe the global variation of the diurnal variation field during disturbed days. For a more complete description of geomagnetic observatory data and the various signals they accommodate, the reader is referred to Matzka et al. (2010) and Love and Chulliat (2013).

3.0 Methodology

The methods adopted for this study is geomagnetic field modelling of the observatory measurements, and cross-correlation analysis. First, a brief modelling approach is given below followed by the cross-correlation analysis approach.

Observatory	IAGA	Country	Region	Colatitude	East Longitude	Institute	GIN
Addis Ababa	AAE	Ethiopia	Africa	80.97°	38.77°	AAU, IPGP	Par
Bangui	BNG	Central African Republic	Africa	85.67°	18.57°	IRD	Par
Mbour	MBO	Senegal	Africa	75.62°	343.03°	IPGP, IRD	Par
Tamanrasset	TAM	Algeria	Africa	67.21°	5.53°	CRAAG,IPGP	Par
Beijing Ming Tombs	BMT	China	Asia	49.7°	116.2°	IGGCAS	Kyo
Phuthuy	PHU	Vietnam	Asia	68.97°	105.95°	VAST, IPGP	Par
Alma Ata	AAA	Kazakhstan	Asia	46.8°	76.9°	IIRK	Edi
Kakioka	KAK	Japan	Asia	53.77°	140.18°	JMA	Kyo
L'Aquila	AQU	Italy	Europe	47.62°	13.32°	INGV	Par
Budkov	BDV	Czech Republic	Europe	40.92°	14.02°	ASCR	Edi
Niemegk	NGK	Germany	Europe	37.93°	12.68°	GFZ	Edi
Belsk	BEL	Poland	Europe	38.16°	20.79°	PAS	Edi
Boulder	BOU	USA	North America	49.86°	254.76°	USGS	Gol
Del Rio	DLR	USA	North America	60.5°	259.08°	USGS	Gol
Ottawa	OTT	Canada	North America	44.597°	284.448°	GSC	Ott
Fresno	FRN	USA	North America	52.91°	240.28°	USGS	Gol

Huancayo	HUA	Peru	South America	102.05°	284.67°	IGP	Edi
Vassouras	VSS	Brazil	South America	112.4°	316.35°	ON, GFZ	Par
Trelew	TRW	Argentina	South America	133.3°	294.7°	UNLP,RMIB	Edi
Kourou	KOU	French Guiana	South America	84.79°	307.27°	IPGP	Par
Gnangara	GNA	Australia	Oceania	121.8°	116.0°	GA	Edi
Guam	GUA	USA	Oceania	76.41°	144.87°	USGS	Gol
Kakadu	KDU	Australia	Oceania	102.69°	132.47°	GA	Edi
Learmonth	LRM	Australia	Oceania	112.22°	114.1°	GA	Edi

Table 1. List of some INTERMAGNET network International Magnetic Observatories (IMOs) used as part of this study. These are the representative observatories for each of the geographical regions of the globe whose results are mentioned in this paper.

3.1 Modelling Approach

For the modelling approach, the method is based on the spherical harmonic modelling of the geomagnetic observatory measurements. The three geomagnetic observatory field components i.e. North (X), East (Y), and vertical downward (Z), were compiled for each of the observatory station measurements. The 'comprehensive approach' was used to co-estimate and parameterize the major geomagnetic field contributions thereby achieving optimal separation of the different field sources (Sabaka et al. 2004, 2002). Since our major interest is in the geomagnetic diurnal variations, which originates primarily from the external field sources, the 'comprehensive approach' using the CM4 model allows us to achieve this. The CM4 codes comes with pre-written driver examples. The 'example 2' driver code is used in this study. It allows the CM4 model to output values of the induced and external components of the field (i.e. ionospheric and magnetospheric) in the three geomagnetic components for a user specified location and time frame for a given time.

In this study, the CM4 model was used in generating all the synthetic measurements. This was done while modifying certain parts of the model (it allows us to) to subtract specific contributions in order to generate the measurements of interest. For this study, we modified the model to generate the specific contributions for two cases of measurements: (a) measurements uncorrected with CM4 (i.e. subtracting field contributions from ionospheric and magnetospheric – raw data, and (b) measurements corrected with CM4 (i.e. contributions from ionospheric and magnetospheric sources included). The measurements generated in each case above for each of the geomagnetic components are compared against the RC index measurements.

3.2 Cross-Correlation Analysis approach

The results from the modelling approach, modelling the geomagnetic observatory component measurements and the RC index are further analysed by means of cross-correlation function/coefficient. Cross-correlation function in geomagnetic field studies provides linear measurements of the correlation between two or more observed quantities.

For this study, we estimated the cross-correlation function between the geomagnetic observatory measurements of the different observatory components and the RC index defined according to Wardinski and Holme (2011)

$$R\ (l) = \frac{\frac{1}{N-l}\sum_{k=l}^{N-l}\{[x(k)].[y(k+l)-\bar{y}]\}}{\sigma_x.\sigma_y} \tag{1}$$

which measures the correlation between two independent series x, y (set as geomagnetic observatory field measurements and the RC index values in this study) with sample length N at sample lag l. σ_x and σ_y denote the standard deviations of the series x and y respectively (we assumed our standard deviation to be 1). A maximum lag, l = 120 was adopted for this study. This was in order to avoid so-called large-lag standard error (Box and Jenkins, 1976), which is 1/11th of the total series length.

The cross-correlation function was plotted as a function of geographical location using the measurements of the different field contributions with the measurements of the RC index. The objective been to establish how widespread and global the nature of the correlation is between the geomagnetic observatory measurements and the RC index.

4.0 Results and Discussion

The results and analysis presented here are for the residual values of the geomagnetic observatory components (X, Y, Z) for the more than 80 observatory stations where measurements were obtained and the RC index. The analysis is based on the comparison of the observatory residual measurements against the RC index. The residuals of the two specific field contributions outlined above (i.e. for measurements corrected and uncorrected with CM4) of the values of the observatory components were individually compared against the residuals of the RC index values.

First, we took a simple running average of about one hour, and then the difference between the running average and what we started with. This was done in order to look at small scale features.

(Note that it is the signals of the difference between the running average and the original measurements time-varying residuals for both the different components of the observatory measurements and the RC index that we are comparing).

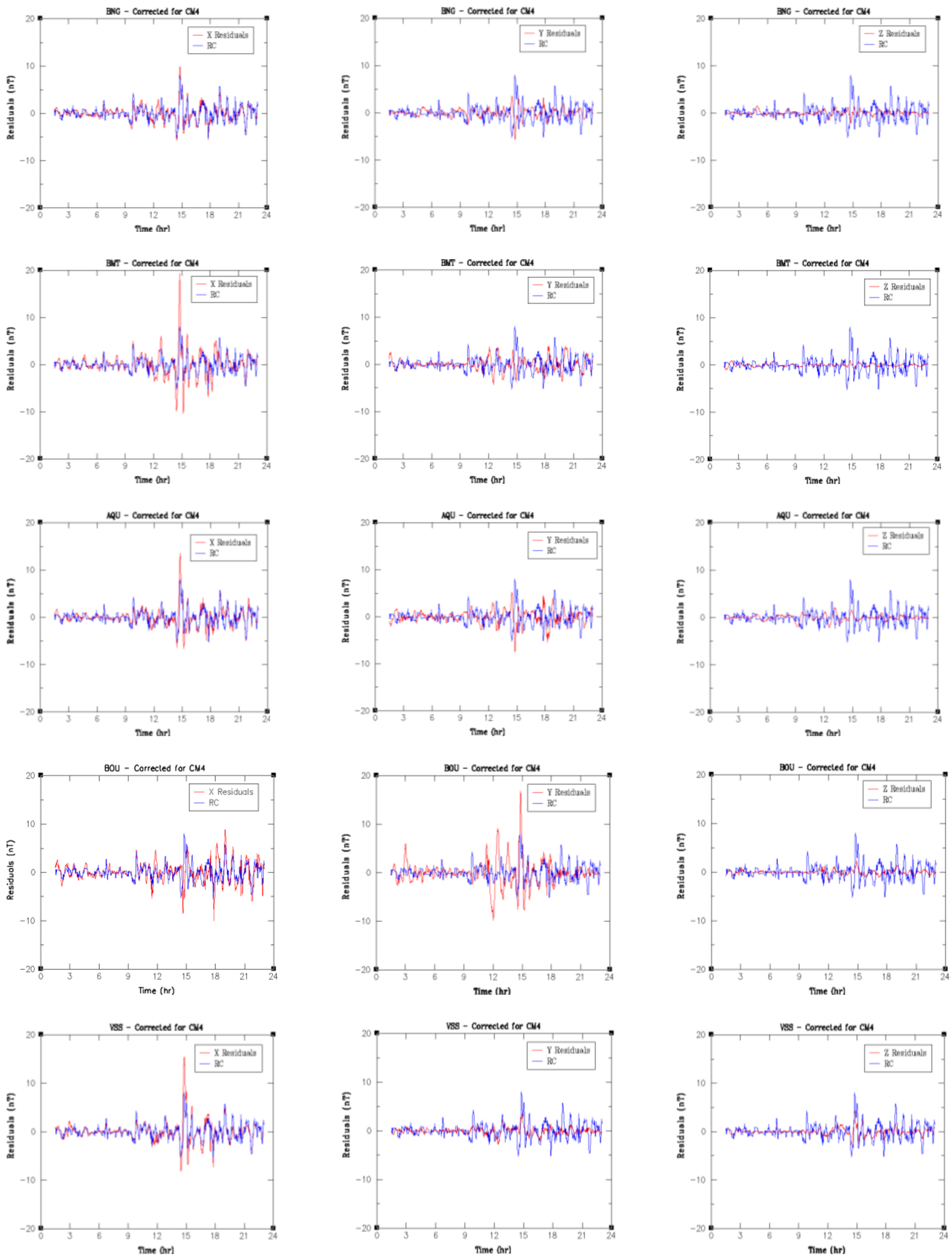
The results for the two different field contributions are outlined below. We have presented results for only selected geomagnetic observatory locations which are representative of each geographical regions.

4.1 Results for Measurements Corrected with CM4

The results of the comparison between the observatory measurement residuals at all observatory locations studied and that of the RC index residuals are shown in figure 1. These observatories are representative of each geographical region, and are for field contributions having ionospheric and magnetospheric sources.

The results obtained for all three geomagnetic observatory components are in reasonable agreement with our expectation, particularly for the X component comparison with the RC index i.e. that the X component would correlate particularly well with the RC index. This is based on the fact that the X component of the observatory measurements is largely more influenced by external field sources (with the magnetospheric ring current being part). This good correlation between the X component residuals is seen in all the observatory station studied across the different parts of the globe. This is confirmed by the representative observatories for the different geographical locations – MBO (Africa), BMT (Asia), NGK (Europe), BOU (North America), VSS (South America), and GNA (Oceania) in figure 1, suggesting that this phenomenon may be global.

Unlike the X component, no obvious trend is observed in the Y and Z components comparison with the RC index. In the Y component, most of the comparison display anti-correlation between the observatory measurement residuals and the RC index. This is particularly seen in BNG, BMT, AQU, and GNA as shown in most of the regional representative geomagnetic observatories seen in figure 1.



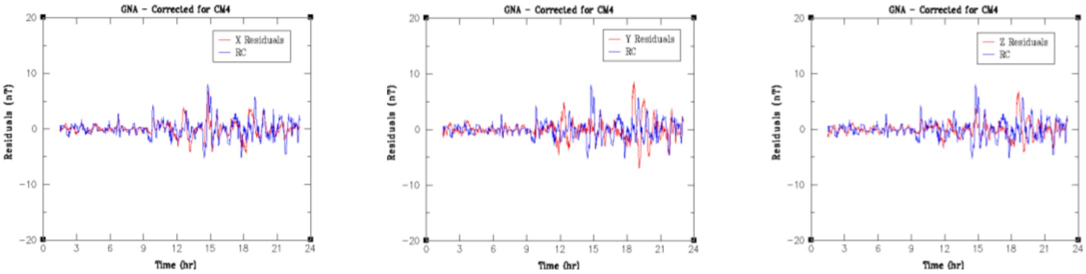


Figure 1. Comparison between X, Y and Z residuals (red lines) corrected for CM4 model (ionospheric and magnetospheric) and RC index residual (blue line) for BNG, BMT, AQU, BOU, VSS and GNA observatory locations. These are for disturbed day 30th May, 2006 with Kp of ≤ 4-.

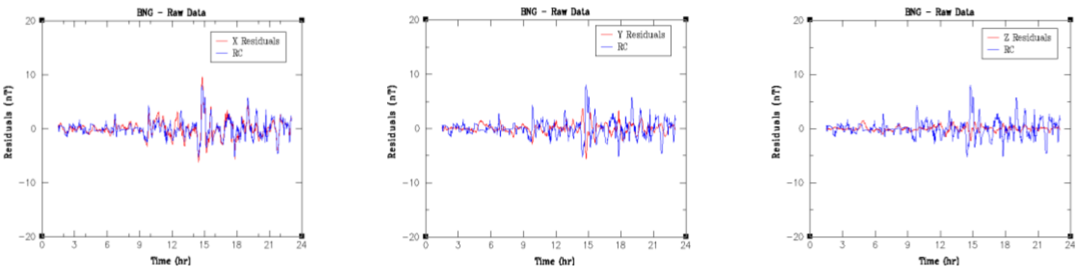
This trend is also seen in most of the observatories across the globe. The Z component of the different observatories also display anti-correlations in most of the observatory locations. There are also a mixture of small correlations and anti-correlations in some of the observatories. This is seen in BOU and AQU, and in most of the obswrvatories in America and Europe studied.

In general, there is no obvious discernible trend in the comparison of the Y and Z components with the RC index. The reasons may be unknown or it may be that the different observatory component measurements are influenced differently by the external field sources, or measurement errors at the different observatory locations, or changes due to induction effect affecting some of the components (i.e. the Z component) more than others.

4.2 Results for Measurements Uncorrected with CM4

Here we look at the comparison between the observatory component measurements and that of the RC index for observatory measurement residuals uncorrected with CM4 i.e. raw data. The results for the comparison are displayed in figure 2 (these are for the regional representative observatories similar to what is presented in figure 1). The results obtained reveal quite similar patterns in the comparison between the observatory component residuals and the RC index in all the observatory locations studied as seen in figure 1.

The X component comparison with RC index follow similar trend in having good correlation in all the observatory locations in the different geographical regions of the Earth. This clearly suggests global phenomenon. The Y and Z component measurements comparison also follow similar trend as in results in figure 1. So, while we can observe clear correlation between the observatory measurements for the X components in all locations, no clear trend in correlation and anti-correlation in the Y and Z components comparison with RC index is observed. In the Y and Z components comparison, we can see the clear reduction in the influence of the external field contributions based on the lack of correlation between the observatory measurement residuals and the RC index. In contrast, the X component measurements displayed a significant level of external field influence notwithstanding the notable level of variability at different observatory locations.



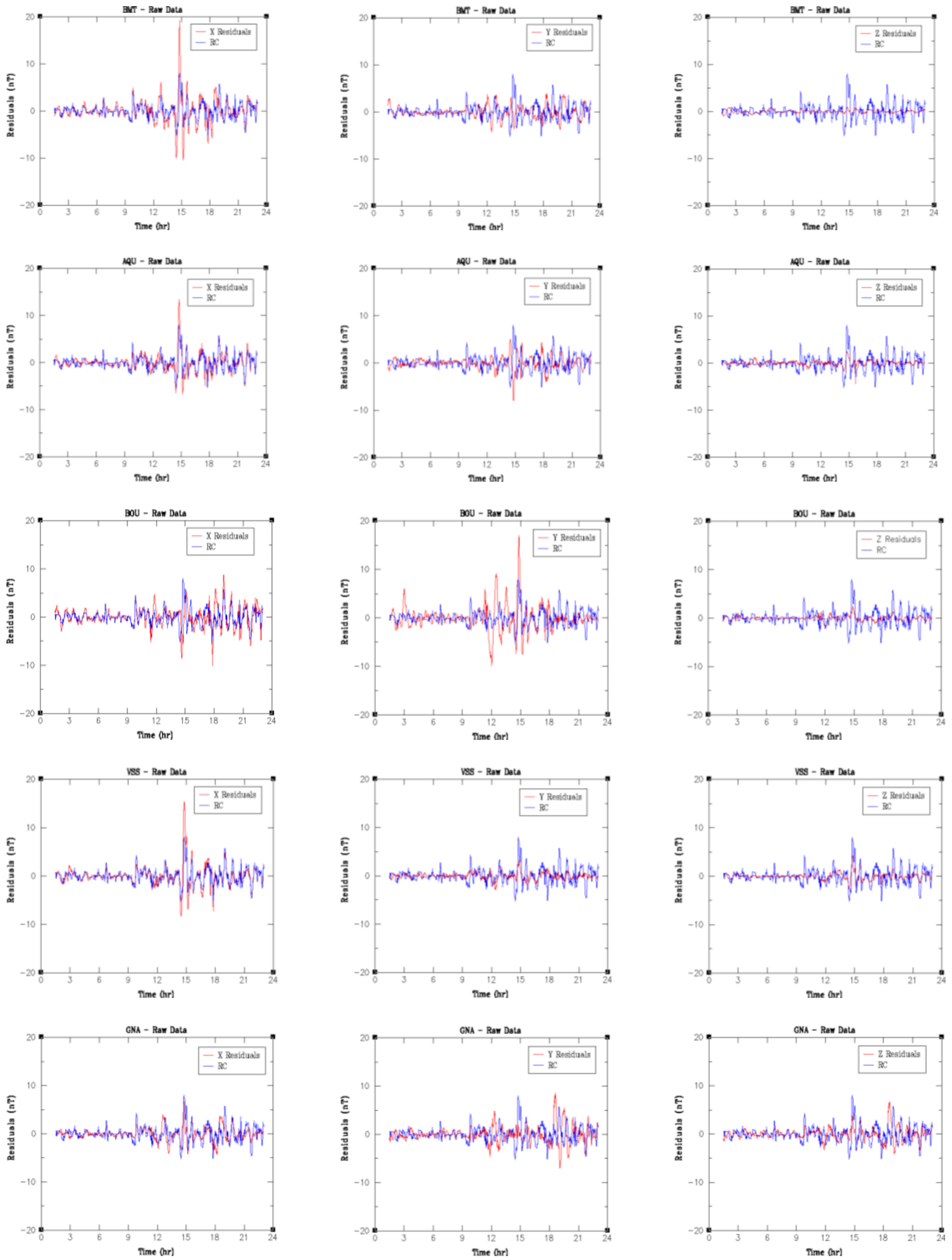


Figure 2. Comparison between X, Y and Z residuals (red lines) uncorrected with CM4 model (raw data) and RC index residual (blue line) for similar observatory locations as in figure 1. Good agreement between X and RC index in all observatories. Anti-correlation observed in Y, and a mixture of good agreement and anti-correlation between Z and RC index.

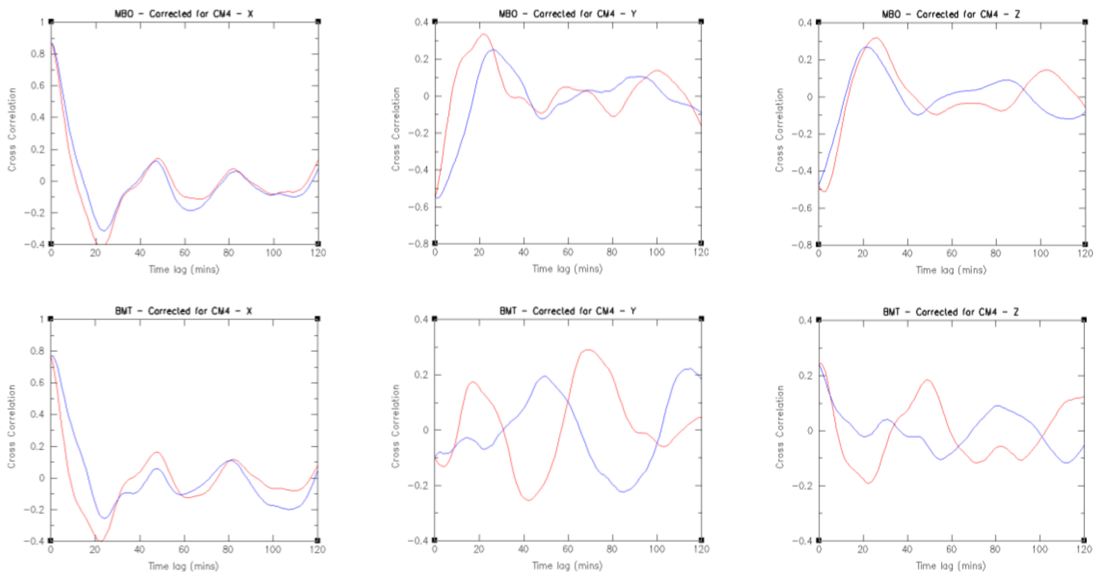
In all the three components (X, Y, Z), the dependence of the variations on geomagnetic and geographic latitude is played out i.e. there is clear coherence between the same geomagnetic observatory components of the field at different observatory locations with largely similar changes in the amplitude variations.

4.3 Cross-Correlation between Observatory Measurement and RC index

To further interpret and explain the results of the modelling of our observatory station measurements, the residuals from all the observatory locations of the geomagnetic field components studied and the RC index were analysed by means of cross-correlation functions. The results of the cross-correlation function are presented in figures 3 and 4. These are for the two cases i.e. measurements residuals corrected with CM4 (having contributions from ionospheric and magnetospheric sources) and raw measurements (no contributions from ionospheric and magnetospheric sources) respectively.

The maxima at zero lag indicate that the variation of the observatory measurement residuals and RC index are correlated or anti-correlated. The cross-correlation coefficient is an estimate that determines the degree of similarity between two independent series that are being compared i.e. x and y. If the series are identical, then the cross-correlation coefficient is 1. To obtain the cross-correlation coefficient, we cross-correlated each of the observatory component residuals with RC, and RC with each of the observatory component residuals (i.e. swapping x and y in equation 1). From their meeting point at zero lag we estimated the cross-correlation coefficient. The results (figures 3 and 4) display similar trends for each of the observatory components at most of the observatory locations between the observatory component residuals and the RC index, irrespective of geographical region.

The results show that the cross-correlation coefficients between the X component residuals and the RC index are largely high at l = 0. The cross-correlation coefficients range between 0.70 and 0.85 exists between the X component residuals and the RC index. Exception to this high cross-correlation coefficient was seen in NGK, BOU, OTT and GNA (see table 2 which shows cross-correlation coefficients from observatory stations from different parts of the globe). Surprisingly, NGK and GNA which are parts of observatories used for constructing the RC index values show somewhat low cross-correlation coefficients, although cross-correlation values of 0.65 and 0.58 for NGK and GNA respectively is still reasonably high (being > 0.5). The low cross-correlation coefficients recorded for BOU (0.45), OTT (0.40) and GNA (0.58) may be due to additional non-coherent, non-RC related signals that may be present in the X component measurement residuals.



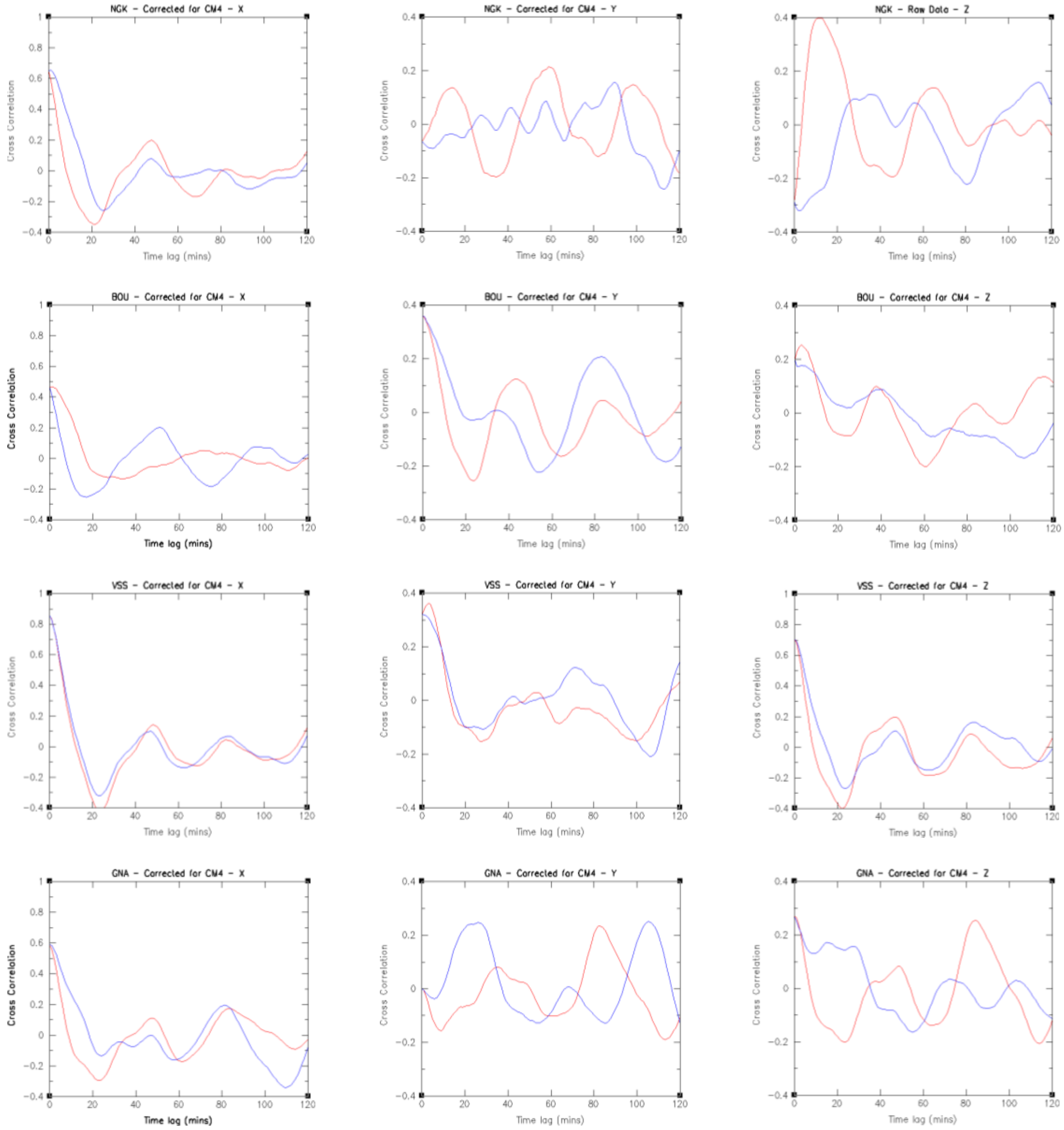
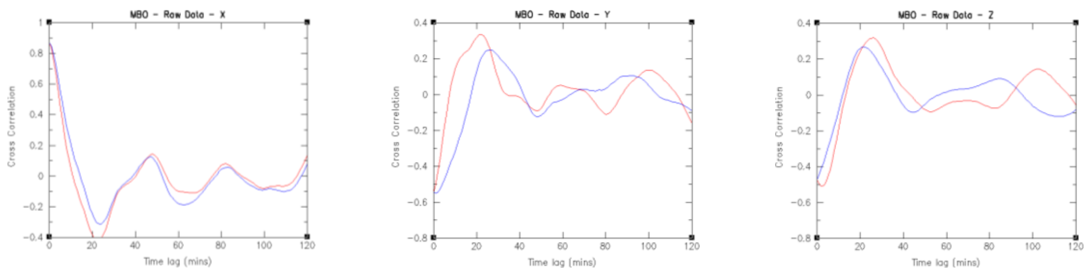


Figure 3. Cross-correlation between X, Y and Z residuals and RC index residual for data corrected with CM4 (ionosphere and magnetosphere) in selected observatory locations in different geographical region of the Earth.



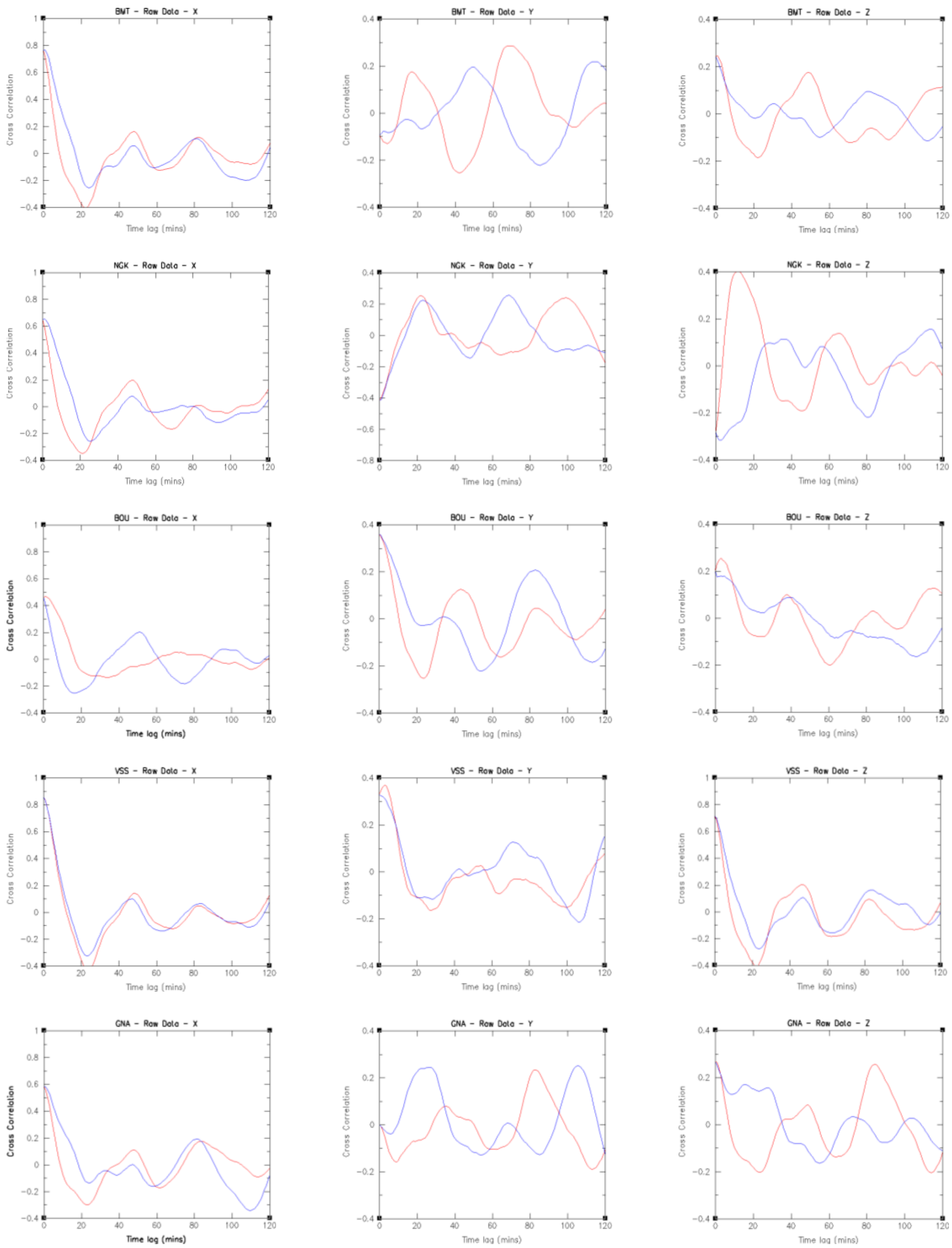


Figure 4. Cross-correlation between X, Y and Z observatory component residuals and RC index residuals for measurement uncorrected with CM4 (raw data) in selected observatory locations in different geographical region of the Earth.

The results also show that irrespective of the field contributions (i.e. measurements corrected with CM4 or measurements uncorrected with CM4 i.e. raw measurements in figures 3 and 4 respectively) there exists generally a high cross-correlation between the X component and the RC index. These cross-correlation coefficients range between 0.80-0.85 for African observatories, 0.75 for Asian, 0.65-0.75 for European, 0.40-0.70 for North American, 0.70-0.85 for South American, and 0.58-0.80 for Oceania observatories. The magnitude of the cross-correlation coefficients across the different observatories show that it does not have any strong geographical dependence. The results follow similar trends in all geographical regions and in the different field contributions. For example, in North America where BOU, OTT, and FRN recorded low cross-correlation coefficients, we can still see DLR in the same region recording cross-correlation coefficients of 0.70, confirming good correlation between the X component and the RC index. The cross-correlation coefficient results as shown by the X component suggests that the rapid variations seen in the observatory measurements during disturbed days may be coming from a large-scale source, possibly ring current magnetosphere, of external origin to the Earth.

Observatory Station	**IAGA Code**	**Correlation Coefficient X with RC Index**	**Correlation Coefficient Y with RC Index**	**Correlation Coefficient Z with RC Index**
Addis Ababa	AAE	0.80	-0.45	0.10
Bangui	BNG	0.85	-0.50	-0.35
Mbour	MBO	0.85	-0.55	-0.50
Tamanrasset	TAM	0.85	-0.55	-0.35
Beijing Ming Tombs	BMT	0.75	-0.10	0.25
Phuthuy	PHU	0.75	0.00	0.60
Alma Ata	AAA	0.75	-0.35	0.55
Kakioka	KAK	0.75	0.15	0.70
L'Aquila	AQU	0.75	-0.55	0.45
Budkov	BDV	0.75	-0.45	0.08
Niemegk	NGK	0.65	-0.40	-0.30
Belsk	BEL	0.70	-0.35	0.20
Boulder	BOU	0.45	0.35	0.20
Del Rio	DLR	0.70	0.50	0.70
Ottawa	OTT	0.40	0.35	0.15
Fresno	FRN	0.55	0.35	0.50
Huancayo	HUA	0.70	0.60	0.70
Vassouras	VSS	0.85	0.35	0.70
Trelew	TRW	0.70	0.15	0.55
Kourou	KOU	0.85	-0.30	-0.70
Gnangara	GNA	0.58	0.00	0.25

Guam	GUA	0.80	0.10	-0.50
Kakadu	KDU	0.70	-0.10	-0.55
Learmonth	LRM	0.65	-0.40	-0.60

Table 2. Cross-correlation coefficients of X, Y and Z components of the geomagnetic diurnal field with the RC index for selected observatory locations in the different geographical regions of the Earth.

Unlike the X component measurement residuals, the RC index variations are not well correlated with the residuals of the Y and Z components. The cross-correlation coefficient range between strong anti-correlation (-0.10 and slightly more than average cross-correlation (0.60) in the Y component, and strong anti-correlation (-0.30) and good correlation (0.70) in the Z component. A few cases of high cross-correlation coefficients can be observed in the Y and Z components, notably in HUA (0.60 and 0.70) in Y component, and DLR, HUA and VSS (all 0.70) in Z component. TRW and VSS recorded values of 0.70 and 0.55 respectively in Y and Z components.

In summary, we observe the cross-correlation coefficients between the X component and the RC index to be good and well correlated in most of the observatory locations studied. This is irrespective of geographical location and field contributions. However, this is not the case in the Y and Z components. This is consistent with the ring current not having any striking effects on the Y and Z components, but affecting the rapid variations observe in the X components of the geomagnetic diurnal variation measurements for disturbed days.

5.0 Conclusions

In this paper, we have investigated how the geomagnetic observatory measurements varies with different field sources during disturbed days, and how the observatory measurements are related to the geomagnetic index, RC for such periods. We studied the coherence and correlation between the components of the observatory measurement residuals and the RC index, and to see if the correlation has global spread.

We performed a cross-correlation analysis comparing the different geomagnetic observatory component measurement residuals and the RC index. The cross-correlation coefficient was derived up to a time lag of 120 minutes (2 hours), with a step of one hour (measurement resolution) in all the investigated cases.

The results clearly show that there is a general coherence and correlation between the residuals of the X component of the observatory measurements and the RC index. This correlation is seen in the observatory station measurements comparison with the RC index in all the geographical regions of the globe, suggesting global phenomenon. This trend is also replicated in the two different field contributions. However, this was not the case for both the Y and Z components as there are no clear trends observed. In the Y and Z components, the result shows a mixture of poor/low correlation and anti-correlation between the observatory component measurements and the RC index. This lack of clear correlation between the Y and Z component measurements and the RC index suggests the lack of influence of the external field variations of ionospheric and magnetospheric sources/contributions.

Confirmation of this good correlation between the X component of the geomagnetic observatory measurements and the RC index is seen in the generally high cross-correlation coefficients in almost all the observatory locations in all the geographical regions of the Earth. On the average, cross-correlation coefficients ranging from 0.70-0.85 was observed for X component in most of the observatories, while for Y and Z components cross-correlation coefficients range between -0.35 and 0.50 in most of the observatory locations.

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