Solar Cycle Variations and Corrected Annual Means for External Effects at Fuerstenfeldbruck 1951 - 1968

U. Schmucker
Institut für Geophysik, Göttingen

1. Introduction

It is well understood that monthly and annual means of magnetic observatories are not completely free of transient effects of external origin. They can arise from annual variations and thus seasonal changes, or from solar cycle variations and thus changing solar activity. Such external effects, together with their internal parts by induction, must be recognized and removed before observatory means yield the true level for the main field and its secular change.

This study concentrates on solar cycle variations and stresses their dual origin: A variable strength of the magnetospheric ring current in the Dst recovery phase of magnetic storms and a variable strength of the ionospheric Sq current system for solar daily variations on quiet days. I shall use the terms "Dst" and "ring current" in a loose sense to identify field variations which could originate from a ring current in the equatorial plane of geomagnetic coordinates, even though other magnetospheric currents may contribute, such as CHAPMAN-FERRARO currents in the magnetopause.

Clearly, Dst and Sq-related contributions to observatory means have quite different source-field geometries. Their separate analysis will be my first goal. This is in essence achieved by considering not monthly or annual means by themselves, but certain differences of them. By working with differences the main field is eliminated and I can avoid in this way also the problematic choice of trend polynoms to approximate the secular change.

A second goal will be to determine Dst-related solar cycle variations in absolute strength in the following sense: Even in quiet times of small solar and magnetic activity, a substantial ring current may exist which would produce an offset between the quiet time level and the true zero reference level for the undisturbed main field. Scott E. Forbush and Lieselotte Beach (1967) have developped an effective method to find such offsets from ground observations which I shall use extensively. Their approach has been confirmed by satellite observations during the MAGSAT mission 1979/80, when for the first time the absolute strength of the ring current could be measured.

Solar cycle variations have internal parts by induction in the electrically conducting earth. In fact, repeated attempts have been made to utilize their exceptionally long periods of eleven years to probe the conductivity deep within the Earth's mantle. However, I shall not consider the induction problem in any detail and simplified preconceived Earth models must suffice to account for internal effects. The interested reader is referred to the cited publications by Isikara (1977) and Ducruix et al. (1980), where further references can be found.

The data to be analysed are from the yearbooks of Fuerstenfeldbruck from 1951 to 1968. Thus, a full solar cycle is included with some additional years at the beginning and end. The maximum at 1957/58 had an exceptionally large sunspot number. Since digital hourly means are not yet available for the selected years, I shall base my study on published and newly derived monthly means.

Data from a single site do not provide much information on the global structure of the variation fields under study. Therefore, I add for the years 1964 and 1965 data from a global network of observatories. They are from Dr. Winch's collection of digital hourly means. Unfortunately, these years contain only small sunspot numbers and thus subdued external effects on monthly and annual means. But at present, there are no other years, for which a comparable thesaurus of digital magnetic observatory data exists.

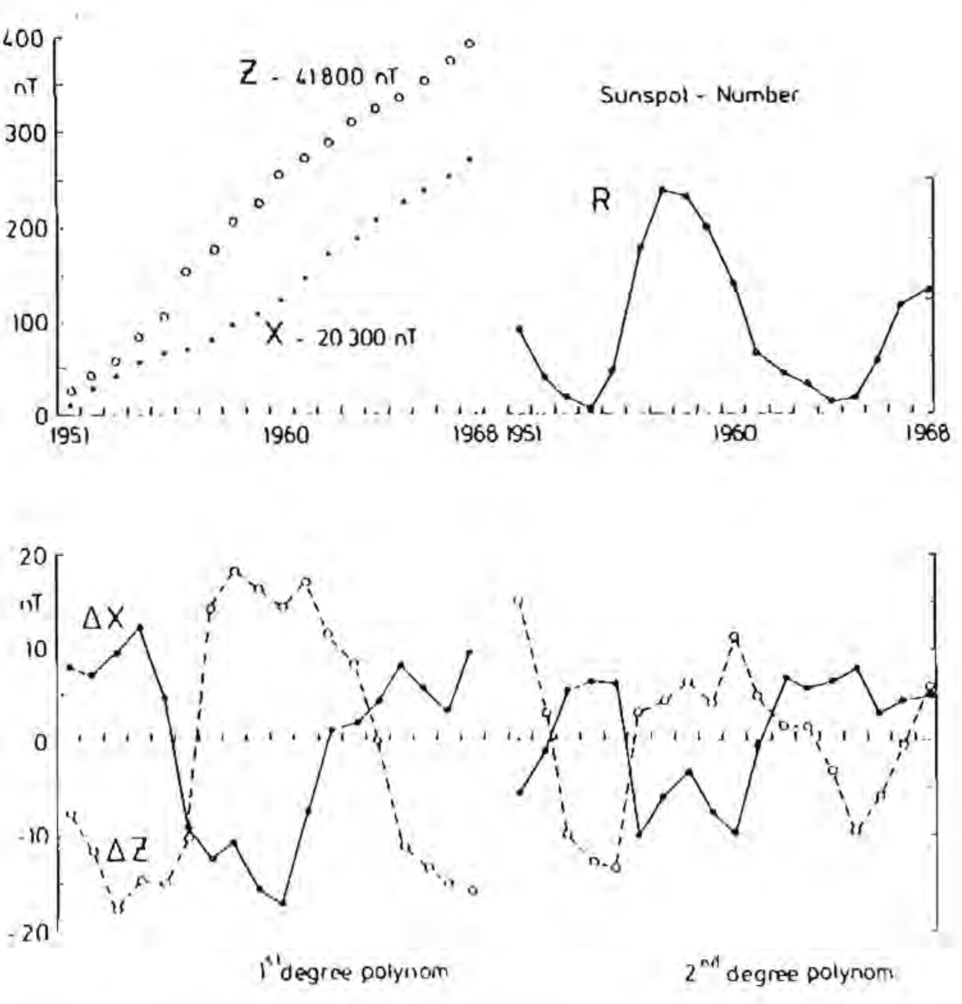

Fig. 1
Top: Annual means Fuerstenfeldbruck, components X and Z, and sunspot numbers R, 1951 - 1968.
Bottom: Deviations of annual means from trend polynoms for the secular change on a tenfold increased scale. The deviations ΔX and ΔZ oscillate with the 11-year period of the sunspot cycle and represent solar cycle variations in their standard definition. Note the dependence on the chosen degree of the trend polynom. - In years following the sunspot number maximum ΔX has its lowest, and ΔZ its highest value, reflecting then a westward ring current of maximum strength. Comparable ΔX and ΔZ amplitudes at this mid-latitude location imply the absence of a significant internal part by induction.

Let me conclude the introduction with some general remarks on solar cycle variations and with a historical note: The standard procedure to identify solar cycle variations consists in a low-order polynomial fit to a sequence of annual means as shown in Fig. 1 for the Fuerstenfeldbruck data. Care has to be taken not to extent the fit over "jerks" in the secular change, for instance the here excluded 1969 jerk. In that year the secular variation in D was abruptly accelerated all over Europe. More on this standard procedure can be found in the cited references by Yukutake (1965), Yukutake and Cain (1979), and Alldredge (1976).

When the polynom is subtracted, the solar cycle variations appear as small ocillations of about 10 nT, following roughly the temporal change of solar activity. Their good spatial correlation is proof that these are not spurious effects, due to local causes such as baseline instabilities, but genuine effects from sources of global dimensions. Fig. 2 in Isikara's publication or Fig. 1 in Voppel's study (1982) are convincing demonstrations of their global character. In any case, trend polynoms cannot remove time-constant external effects, arising for instance from a steady ring current, which would result in invisible offsets between the trend polynom and the true level of the main field.

Sofar interest has been focussed on Dst-related solar cycle variations and in most publications the possibility of substantial contributions from Sq is ignored. Voppel, on the other hand, refers already explicitly to Sq effects in his concluding remarks. That they exist should be obvious from the fact that in particular Sq variations in H and Z possess non-vanishing daily means, when they are measured against the midnight level. Since Sq varies with the seasons, monthly means should move up and down within a year, and since Sq varies also with solar activity, annual means should do the same with the 11-year period of the sunspot cycle.

It is important to note that not even the local night field is without Sq contributions. Overhead Sq currents may be absent during the night hours, but internal currents by induction flow at all times, including midnight. A.A. Ashour and Anthony T. Price (1965) have argued convincingly, why such internal midnight current must exists, even though there is no direct way to measure them.

Now the historical note: The knowledge of solar cycle effects on daily variations dates back to the times, when continuous magnetic observations began. Schwabe's discovery of the solar cycle was followed within a few years by the discovery of a solar cycle effect on the amplitude of solar daily variations. The following excerpts from the fourth volume of A.v. Humboldt's Kosmos in the edition of 1874, published by J.G. Cotta, refer in this context distinctly to the founding father of the Fuerstenfeldbruck observatory, Johann Lamont:

"Der muthmaßliche Zusammenhang zwischen der periodischen Zu- und Abnahme der Jahresmittel der täglichen Declinations-Variation der Magnetnadel und der periodischen Frequenz der Sonnenflecken ist zuerst von Oberst Sabine in den Phil. Transact. for 1852; und, ohne daß er Kenntniß von dieser Arbeit hatte,

4 bis 5 Monate später von dem gelehrten Director der Sternwarte zu Bern, Rudolf Wolf, in den Schriften der schweizerischen Naturforscher verkündigt worden. Lamont's Handbuch des Erdmagnetismus (1848) enthält die Angabe der neuesten Mittel der Beobachtung wie die Entwickelung der Methoden." (p. 49/50)
"Nach Lamont und Reslhuber ist die magnetische Periode 10 1/8 Jahre: so daß die Größe des Mittels der täglichen Bewegung der Nadel 5 Jahre hindurch zu- und 5 Jahre hindurch abnimmt, wobei die winterliche Bewegung (amplitudo der Abweichung) immerfort fast doppelt so schwach als die der Sommermonate ist. (Vergl. Lamont, Jahresbericht der Sternwarte zu München für 1852 S. 54-60.) Der Director der Berner Sternwarte, Herr Rudolph Wolf, findet durch eine viel umfassendere Arbeit, daß die zusammentreffende Periode der Magnet-Declination und der Frequenz der Sonnenflecken auf 11,1 Jahr zu setzen sei." (p. 134)

2. Monthly Mean Values Fuerstenfeldbruck 1951 - 1968

The yearbooks contain the monthly means of the three geomagnetic elements DHZ, separately derived by averaging the daily means of all days, of the five most quiet days (Q-days) and the five most disturbed days (D-days). I have calculated additional monthly means for local midnight, again separately for all days, Q-days and D-days. The midnight values are averages of the intervall from 0 h to 3 h Greenwich time, centered at 1:30 Greenwich time or 2:15 local time at 11.28° eastern longitude. All D and H means have been converted to X (northcomponent) and Y (eastcomponent) in geographic coordinates.

Mean values need trend corrections for non-cyclic changes, when studying Sq. Except for D-days, non-cyclic changes are quite systematic in size and sign, both consistent with a smooth day-by-day decrease of an equatorial ring current. Fig. 16 in chapter IX of Chapman and Bartels' treatise (1940) exemplifies this observation which has been investigated thoroughly on a global scale by Grafe (1964).

Let f_0, f_1, ... f_{23} be the 24 tabulated hourly mean values of a selected Greenwich day; f_0 is the mean of the first and f_{23} the mean of the last hour of that day, centered at 0^{30} UT and 23^{30} UT, respectively. With f_{24} as the mean of the first hour of the following day, $2d = f_{24} - f_0$ defines the non-cyclic change of the selected day.

Then, with N = 24, the trend to be removed, is $g_n = d\cdot(2n/N - 1)$.
Clearly,

$$\sum_{n=0}^{N} g_n = 0 \quad \text{and} \quad \sum_{n=0}^{N-1} g_n = -g_N = -d,$$

which gives as trend-corrected daily mean

$$F' = 1/N \sum_{n=0}^{N-1} (f_n - g_n) = F + d/N,$$

when F is the original uncorrected daily mean from the tables.

Let 2M + 1 be the number of hourly values, from which a local midnight average is formed. Let f_r be the hourly value in the center of the averaging interval, chosen in such a way that f_r refers as closely as possible not to local midnight, but to 2 hours in the morning local time. Here M = 1 and, in the case of Fuerstenfeldbruck, r = 1.

The midnight average from the tabulated hourly means is

$$F_M = 1/M \sum_{k=-M}^{+M} f_{r+k}.$$

Observing that

$$\sum_k g_{r+k} = 2\ d \cdot M\ (2r/N - 1),$$

the trend-corrected midnight average becomes

$$F'_M = F_M + 2d\cdot(1 - 2r/N).$$

Obviously no correction is needed for r = 12, when the center of the midnight interval is at 12 hours Greenwich time. Otherwise the correction may be quite substantial, at least much larger than the correction for daily means.

Because the yearbooks do not list the 25th value of the day, I have derived the non-cyclic change for simplicity from $f_{23} - f_0$. This allowed me to use the hourly values, averaged over the month, at the bottom of each table. Also the corrections were not applied individually to the selected days, but to their monthly averages.

To distinguish between the various types of monthly means, I use the following code: Letter A refers to the means of all days, letter Q and D to those of Q-days and D-days, respectively. An added letter M implies that midnight averages are used. For example, X(Q) is the monthly average of the five Q-day daily means, X(QM) is the monthly mean of the daily midnight averages of the same Q-days.

Fig. 2 to 4 represent resulting sequences of monthly values. To suppress the otherwise dominating secular change, trend polynoms have been removed beforehand. These are best fitting polynoms of first or second degree through the respective eighteen annual means. As seen by comparing Figs. 2 and 3, linear trends as in Fig. 2 are adequate for the secular changes in X and Z. In Y the non-linearity of the secular change is strong and a second degree polynom is needed to produce a flat curve. Thus, from 1951 to 1968 we have a continuous slow-down in the secular variation of Y.

The expected solar cycle variations are clearly seen in X and Z, regardless of how the monthly means were formed. In Y only irregular variations are observed. Naturally, as Fig. 3 shows, the solar cycle variations are strongest, when D-days are used alone. But they are still visible, when the monthly means are derived from Q-days only, a first indication for a non-vanishing ring current in times of magnetic quietness.

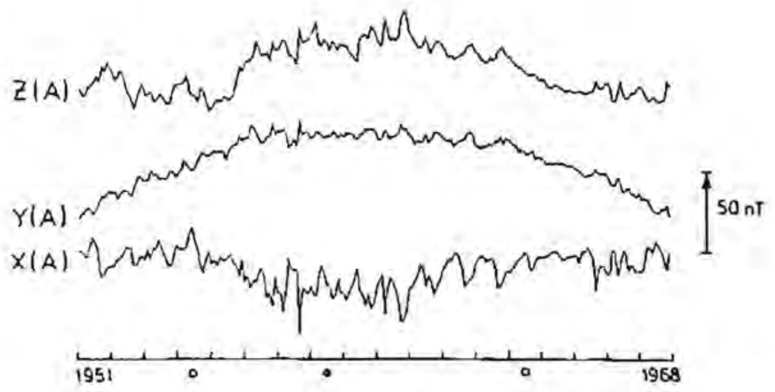

Fig. 2
Fuerstenfeldbruck monthly means from all days, 1951 - 1968 after subtracting linear trends for the secular change. Here and in the following illustrations open and closed circles indicate years of minimum and maximum sunspot numbers, respectively. Clearly visible modulation in X and Z with the 11-year solar cycle. Irregular variations in Y are superimposed on a curved background, indicating a continuous slow-down of secular variations in this component.

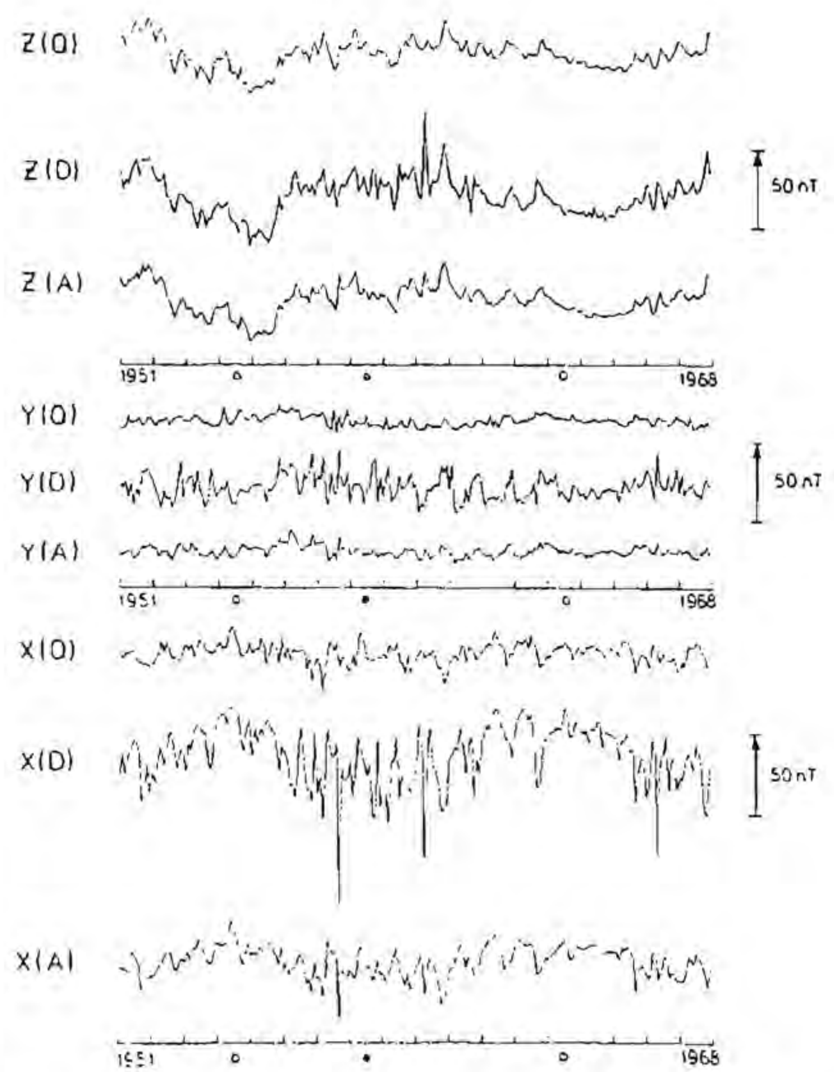

Fig. 3
Fuerstenfeldbruck monthly means 1951 - 1968 from all days, D-days, and Q-days after subtracting second degree trend polynoms for the secular change. All three types of monthly means in X and Z show again the 11-year period of the solar cycle, but the strongest oscillations occur when the monthly means are for D-days. Non-zero solar cycle variations for Q-days indicate ring current effects even on days with small magnetic activity.

It can be seen that the sunspot maximum of 1957/58 coincides well with a minimum of monthly means in X, while the sunspot minima 1954 and 1964 concur with maxima. The departures in Z from the trend polynom follow an opposite trend with a comparable peak-to-peak amplitude. This agrees with the field geometry of an equatorial ring current, flowing eastward and modulated by solar activity. A Z:X ratio near unity in midlatitudes suggests that no substantial internal dipole source by induction exists, which would have increased X over Z (cf. Eq. 2).

The exclusive use of midnight averages of quiet days as in Fig. 4 uncovers otherwise invisible annual variations of the monthly means. As already pointed out, they arise from the seasonal dependence of Sq and are exclusively of internal origin. But this is only a side remark because annual variations will not be dealt with any further.

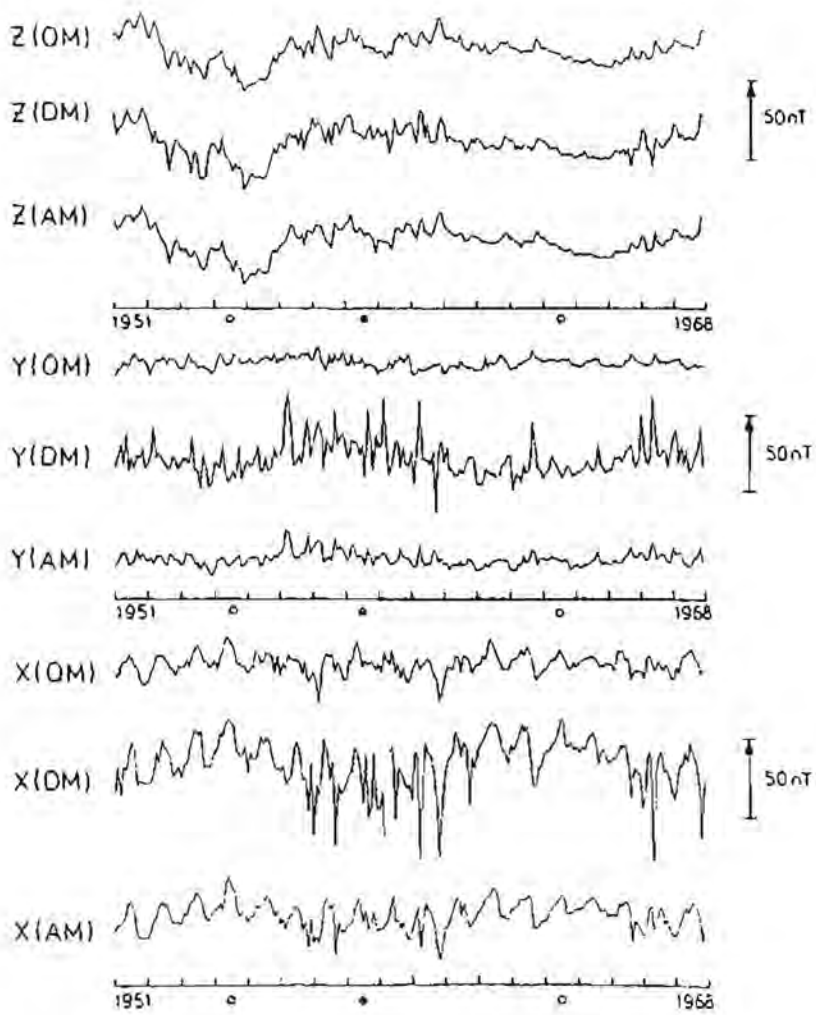

Fig. 4
Same as in Fig. 3, but with monthly means of midnight values. In addition to solar cycle variations now annual variations appear, which are best seen in years with small sunspot numbers. They can be associated with internal Sq-variations at local midnight.

3. Dst-related Contributions to Monthly Means

I start with the simplifying assumption that, for a given month, solar daily variations are the same on D and Q days. Then they are eliminated by taking the difference of D-day and Q-day monthly means. For brevity their difference will be written as

$$X(D-Q) = X(D) - X(Q),\ Y(D-Q) = \cdots,\ Z(D-Q) = \cdots .$$

The assumption ignores the existence of S_D during disturbed days and will fail in high latitudes. In lower latitudes, however, S_D is small and continuous plots of such differences as in Fig. 5 reveal that part of solar cycle variations which is related to Dst. Since the ring current flow is controlled by the Earth's dipole field, horizontal components with respect to geomagnetic coordinates are displayed in this figure.

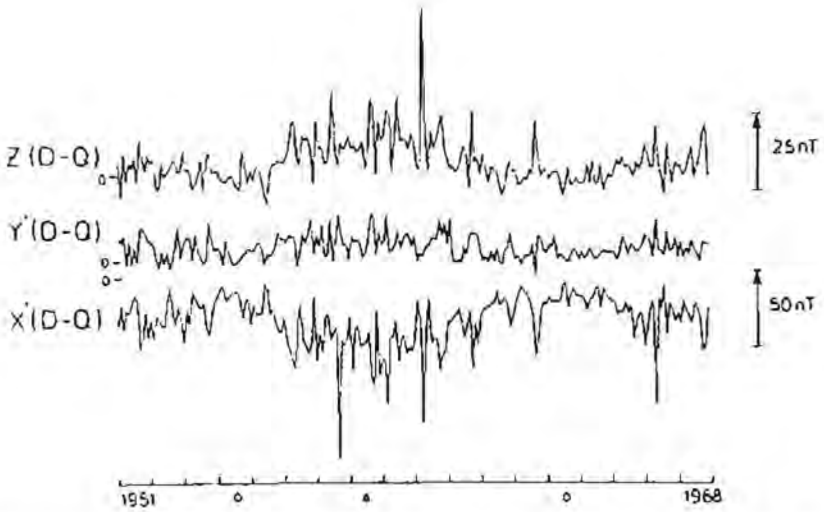

Fig. 5
Fuerstenfeldbruck monthly mean differences of D-days and Q-days 1951 - 68. According to the Forbush relations (5), they are proportional to the absolute strength of the ring current and define the Dst corrections to monthly and annual means. Note the predominance of the 11-year period of the solar cycle and the absence of annual variations.

Fig. 6 explains schematically, how the difference of monthly means is to be interpreted, using X as an example. In this figure X* indicates the true zero reference level for the undisturbed main field without external effects. For simplicity, no secular change is assumed and X* is shown as a horizontal line. Then the monthly means X(Q) define for each month a second level below X* due to the quiet time ring current, here taken to be flowing westward. D-days fall in the main phase or in the early part of the Dst recovery phase of magnetic storms. Therefore X(D) defines a third level, which because of the intensified ring current during disturbed days lies even deeper than X(Q). Nearly without exemptions monthly differences X(D-Q) are indeed negative as seen in Fig. 5.

During the sunspot cycle the X* level remains fixed (in the assumed absense of secular variations), while the X(Q) and X(D) levels move up and down with changing solar activity. It is sensible to assume that the differences X(D-Q) are largest for maximum activity and vice versa as shown in the lower graph of Fig. 6.

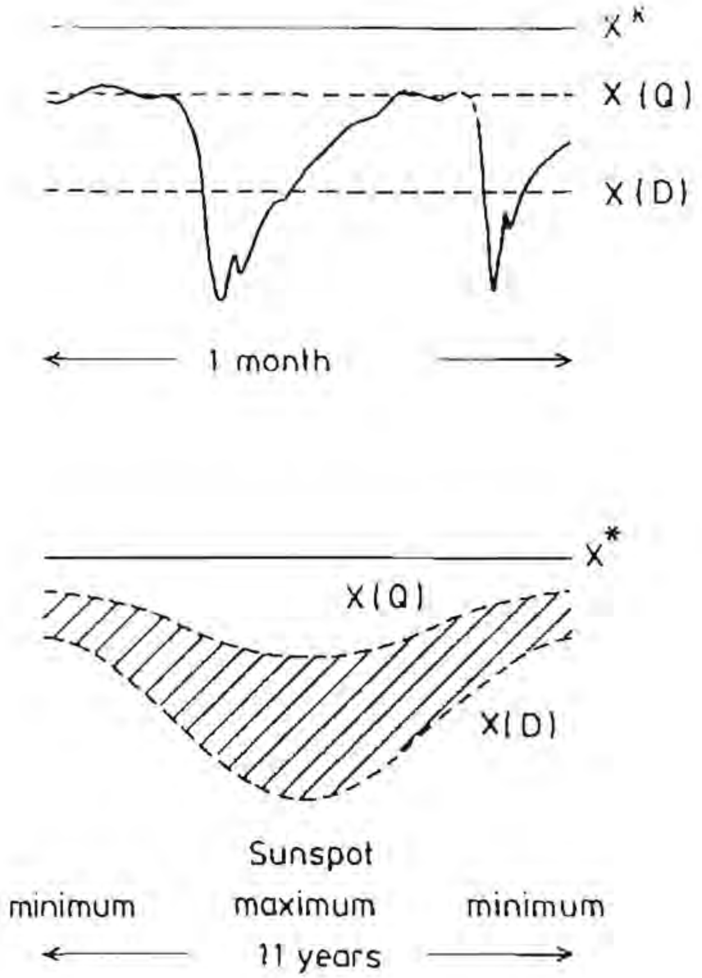

Fig. 6
Top: Monthly mean level of D-days and Q-days in X against the true zero level X*, with a schematic explanation by magnetic storms, omitting Sq. - Bottom: The same levels in motion during the solar cycle, assuming an offset against true zero even in years of minimum sunspot number.

Forbush and Beach (1967) introduced now the key hypothesis that the departures of X(Q) and X(D) from X* maintain a fixed ratio to eachother throughout the solar cycle. Their hypothesis implies that the ring current field on quiet days is a constant fraction of the ring current field on disturbed days and that the same applies to their internal parts. Denoting with X_{RC} the sum of external and internal parts, the first hypothesis reads

$$X_{RC}(Q) = k \cdot X_{RC}(D),$$

or rewritten in terms of their difference,

$$X_{RC}(Q) = k/(1-k) \cdot (X_{RC}(D) - X_{RC}(Q)). \qquad (1)$$

By equating $X_{RC}(D) - X_{RC}(Q)$ with X(D-Q) the absolute ring current field can be estimated from observatory data, once an appropriate value for k has been found.

The second hypothesis is that k is a universal constant. This implies basically that the geometry of the ring current field is the same throughout the solar cycle and the same on Q and D-days.

Forbush and Beach tested both hypotheses with annual means of selected observatories in different latitudes. Care was taken that the observatories had constant secular variations. Let $\langle X(Q)\rangle$ denote the meanvalue of the annual means $X(Q)$ over all years used. Plotting then $X(Q) - \langle X(Q)\rangle$ against $X(D-Q)$ gave a striking linear relation which proved the first hypothesis. Then the same regression line was found to fit for all observatories which proved the second hypothesis and allowed an estimate of the universal constant k. The quoted numerical value is $k/(1-k) = 0.68$.

An extension to the vertical component requires either a new analysis with annual means in Z or explicit assumptions about the source geometry and about the conductivity within the Earth. I choose the second alternative and assume a ring current potential

$$U_{RC} = R\ \{(r/R)\cdot E + (R/r)^2 \cdot I\}\ \cos\theta$$

with R as Earth radius and θ as colatitude; E and I are the potential coefficients for external and internal sources, respectively. The external source field is uniform, the internal field a dipole field. For $r = R$ the components of the surface field follow as

$$X_{RC} = +R^{-1}\ \delta U_{RC}/\ \delta\theta = -(E + I)\ \cdot \sin\theta$$

$$Z_{RC} = +\ \delta U_{RC}/\ \delta r\ = +(E - 2I)\cdot \cos\theta. \qquad (2)$$

I apply now the Forbush relation (1) to the external potential coefficient and define a new factor k' in

$$E(Q) = k' \cdot E(D) = (k')/(1-k') \cdot E(D-Q) \qquad (3)$$

with $E(D-Q)$ standing again for $E(D) - E(Q)$. To account for internal induction, let $S = I/E$ be the potential ratio of internal to external parts. This ratio will be regarded as a time-independent global constant. The pertinent Earth model for $S>0$ has zero conductivity down to a certain depth z^* and then infinite conductivity. This perfect substitute conductor for the real Earth reflects the depth of penetration and therefore z^* must increase with increasing slowness of the variations.

Let, in general, n be the degree of the spherical harmonics describing the surface field potential (here $n = 1$). Then the definition of penetration depth C in terms of S is

$$C := R/(n+1)\cdot \{1-(n+1)/(n)\cdot S\}/\{1 + S\}. \qquad (4)$$

In case of a static field and no induction ($S = 0$), C has its greatest value $R/(n+1)$. If C is small against R, then C becomes identical with the depth z^* of a perfect substitute conductor because in that case

$$S = n/(n+1)\cdot \{(R-z^*)/R\}^{2n+1} \approx n/(n+1)\cdot \{1-(2n+1)\ z^*/R\}.$$

I assign now a ratio S_1 and a resulting penetration depth C_1 to the ring current on quiet days, which oscillates with the 11-year period of the solar cycle, and a ratio S_2 and depth C_2 to the recovery phase of individual storms. Obviously C_1 exceeds C_2 since this recovery occurs within days instead of years.

Inserting $I(Q) = S_1 E(Q)$ and $I(D-Q) = S_2 E(D-Q)$ into (2) gives

$$X_{RC}(Q) = -E(Q) \cdot (1+S_1) \sin\theta,$$
$$X_{RC}(D-Q) = -E(D-Q) \cdot (1+S_2) \sin\theta$$

and thereby with (3)

$$X_{RC}(Q) = k'/(1-k') \cdot (1+S_1)/(1+S_2) \cdot X_{RC}(D-Q).$$

Similarly for Z we obtain

$$Z_{RC}(Q) = k'/(1-k') \cdot (1-2\ S_1)/(1-2\ S_2) \cdot Z_{RC}(D-Q).$$

By comparison with (1) it follows that

$$k'/(1-k') \cdot (1+S_1)/(1+S_2) = k/(1-k)$$

and from (4) with n=1 that

$$k'/(1-k') \cdot (1-2\ S_1)/(1-2\ S_2) = k/(1-k) \cdot C_1/C_2.$$

In summary, the absolute ring current field with its internal part by induction can be derived by applying the Forbush relations

$$X_{RC}(Q) = k/(1-k) \cdot X(D-Q)$$
$$Z_{RC}(Q) = k/(1-k) \cdot \beta \cdot Z(D-Q) \qquad (5)$$

to data of a single observatory, assuming k and $\beta = C_1/C_2$ to be universal constants. In this sense, the monthly differences in Fig. 5 provide a direct measure for the changing absolute strength of the ring current from 1951 to 1968.

4. Sq-related Contributions to Monthly Means

In order to limit this section to genuine Sq variations, I shall use monthly means from quiet days only. I presume that any Dst-related part has been removed by corrections for the non-cyclic change as described in section 2. Let then again X*, Y*, Z* be the zero reference levels for the undisturbed main field. Departures from them, say $X_{SQ}(t) = X(t) - X^*$, define the true mean Sq variations of the respective month in Greenwich time t from midnight to midnight. Let $\langle X_{SQ} \rangle$ denote the daily mean value of $X_{SQ}(t)$ and let $t = t_0$ be local midnight. Then, with corresponding notations for Y and Z, the Sq-related contributions to monthly means in X are $\langle X_{SQ} \rangle = X(Q) - X^*$ and $X_{SQ}(t_0) = X(QM) - X^*$, approximating the instant midnight value $X(t_0)$ with the midnight intervall average X(QM) from Section 2.

Non-vanishing daily means in X and Z arise from the fact that their departures from true zero are mainly in one direction, i.e. $X_{SQ}(t)$ and $Z_{SQ}(t)$ are either positive or negative throughout the day with peak values near local noon. In Y these departures have opposite signs before and after local noon and tend to average out over the day.

Non-vanishing midnight values $X_{SQ}(t_0)$ and $Z_{SQ}(t_0)$ are not obvious and need an explanation: Fig. 7 shows schematically the Sq variations in X at a low latitude site. Thus, $X_{SQ}(t)$ is shown positive at daytime with a maximum at noon, reflecting the eastward flow of external and westward flow of internal currents near to the equator. The resulting daily mean $\langle X_{SQ}\rangle$ is positive which places X(Q) above the reference level X*.

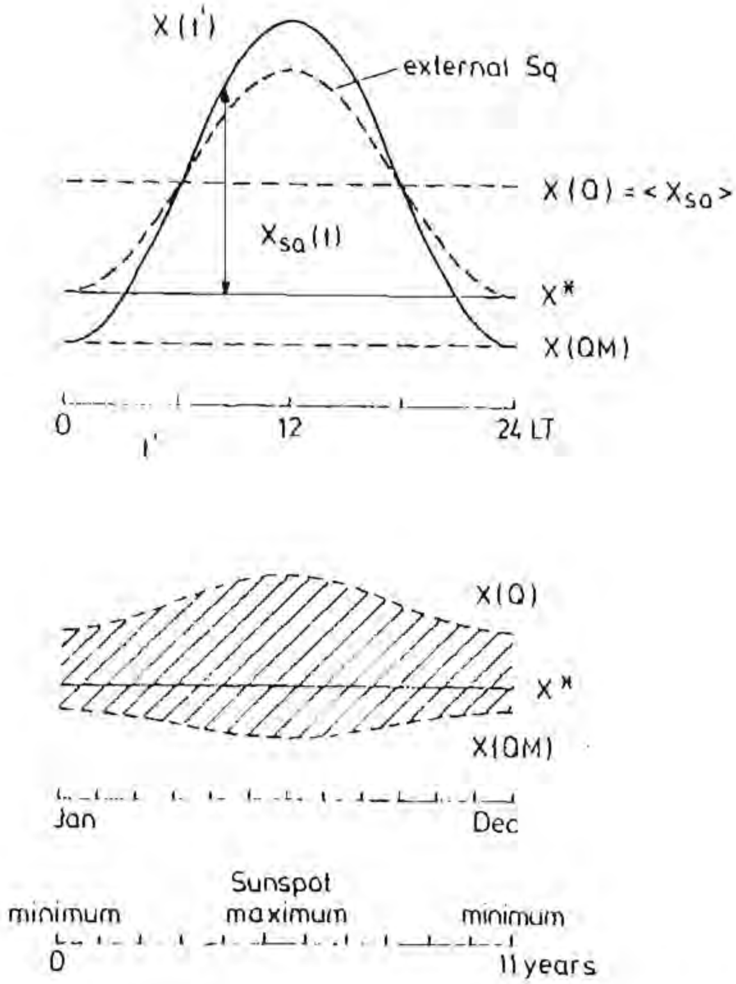

Fig. 7
Top: Daily mean level and local midnight level in X on Q-days against the true zero level X*, with a schematic explanation by the external and internal parts of Sq.
Bottom: The same levels in motion during the year and during the sunspot cycle.

At midnight the total X_{SQ} as sum of external and internal parts is not assumed to be zero, as the absence of overhead currents during the night might have suggested, but as negative which places X(QM) below X*. This is done to account for an eastward internal current flow across the midnight meridian. Ashour and Price's arguments for this current can be simplified as follows:

Sq variations consist of external and internal parts, say $X_{SQ} = X_{SQ}^{(e)} + X_{SQ}^{(i)}$. Let the conducting Earth be again of zero conductivity down to a certain depth and then perfectly conducting. Then internal and external parts have a constant potential ratio S, but only after any time-constant portion in the external part has been subtracted. A static field simply does not induce currents.

Since Sq variations follow in sequence day after day, the time-constant portion is the daily mean of the external field, if the day-to-day variability of Sq is ignored. Because the internal field has no time-constant portion, the daily means of the external and total Sq variations are identical. Hence,

$$H_{SQ}^{(i)} = S \cdot (H_{SQ}^{(e)} - \langle H_{SQ} \rangle).$$

Suppose that the external Sq field is zero at local midnight. In the case of X this implies that no overhead Sq currents cross the midnight meridians which is reasonable to assume. For Z the implications are more complicated but also justifiable. Then, as shown in Fig. 7, the external Sq variations start at midnight on the X* level while the total Sq variations begin below this level because $X_{SQ}^{(i)}(t_0) = -S \cdot \langle X_{SQ} \rangle$ is negative. This explains the postulated internal current flow across the midnight meridian in the absence of overhead currents.

In summary, only external Sq variations contribute to the daily mean and only internal Sq variations to the midnight value, provided that the external Sq is then zero. We assume this to be case. Then the difference of daily mean and midnight value defines in its external and internal parts the daily mean and midnight value of the Sq variations, i.e. from $X(Q\text{-}QM) = \langle X_{SQ} \rangle - X_{SQ}(t_0)$ in the case of X follows

$$\begin{aligned} X(Q\text{-}QM)_{ext} &= \langle X_{SQ} \rangle, \\ X(Q\text{-}QM)_{int} &= -X_{SQ}(t_0). \end{aligned} \tag{6}$$

Hence, the Sq-related contributions to the monthly means X(Q) and X(QM), given by $\langle X_{SQ} \rangle$ and $X_{SQ}(t_0)$, are found without any further assumptions by conducting a global separation analysis with the above differences in X, Y, Z. For a fixed source geometry the equations for the daily means can be written as

$$\begin{aligned} \langle X_{SQ} \rangle &= q_X \cdot X(Q\text{-}QM) \\ \langle Y_{SQ} \rangle &= q_Y \cdot Y(Q\text{-}QM) \\ \langle Z_{SQ} \rangle &= q_Z \cdot Z(Q\text{-}QM) \end{aligned} \tag{7}$$

with constant factors q_X, q_Y, and q_Z for a given season and location. In this way the differences of monthly means as shown in Fig. 8 display the changing contributions of Sq to monthly and annual means. Once the q-factors are known, these contributions are readily found.

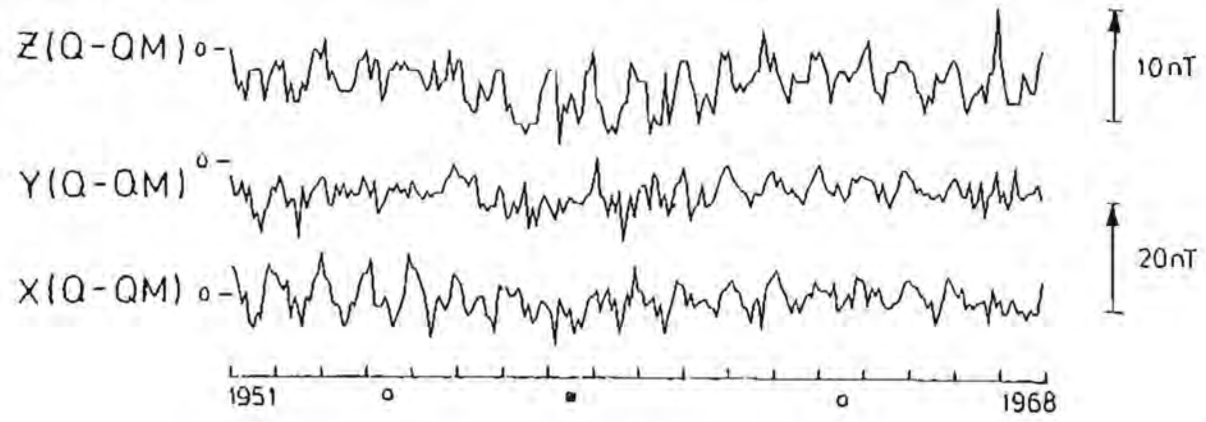

Fig. 8
Fuerstenfeldbruck monthly mean differences of daily means and midnight values on Q-days 1951 - 68. According to (10) they measure the departure of the daily mean of Sq from true zero, yielding thereby the Sq-corrections for monthly and annual means. Note the annual variations in all components, while solar cycle variations are visible only in Z which reflects the mid-latitude position of Fuerstenfeldbruck near to the center of the northern Sq current vortex.

Estimates of these factors without separation analysis require explicit assumptions about the time-space structure of the global Sq field and about the induction by Sq. Suppose that the Sq variations depend solely on local time t', and let the colatitude dependence of their potential U_{SQ} for the m-th time harmonic be expressed by a single spherical harmonic, namely $P_{m+1}{}^{m}(\cos\theta)$. I shall approximate for simplicity Sq variations by their first time harmonic and obtain with m = 1 and $P_2{}^1 \sim \sin 2\theta$

$$U_{SQ} = R\ \{(r/R)^2 \cdot E(t') + (R/r)^3 \cdot I(t')\}\ \sin 2\theta.$$

For calculations with a more realistic time-space structure and with Earth models of finite conductivity the reader is referred to the original work of Ashour and Price (1965).

To have vanishing external fields at midnight, I set

$$E(t') = E_0\ (1-\cos t')$$

with t' in angular measure, i.e. t' = 0 corresponds to local midnight and t' = π to local noon. The daily mean of E(t') is E_0 and thereby the internal potential coefficient

$$I(t') = S \cdot (E(t') - E_0) = -S \cdot E_0 \cos t'.$$

The resulting surface field components are

$$X_{SQ} = R^{-1}\ \delta U_{SQ}/\ \delta\theta = 2E_0\{1-(1+S)\quad \cos t'\}\cos 2\theta$$
$$Z_{SQ} = \quad \delta U_{SQ}/\ \delta r \quad = 2E_0\{1-(1-3/2\ S)\cos t'\}\sin 2\theta \qquad (8)$$

at $r = R$. We infer

$$<X_{SQ}> \ = \ 2E_0 \cos 2\theta,\ <Z_{SQ}> \ = \ 2E_0 \sin 2\theta$$

for the external daily means and

$$X_{SQ}(O) = -2\ S\cdot E_0 \cos 2\theta,\ Z_{SQ}(O) = \ 3\ S\cdot E_0 \sin 2\theta$$

for the internal midnight values. Since Y_{SQ} is proportional to sin t', its daily mean and midnight values are both zero. Consider now the differences

$$<X_{SQ}> - X_{SQ}(O) = \ 2E_0(1+S) \qquad \cos 2\theta,$$
$$<Z_{SQ}> - Z_{SQ}(O) = \ 2E_0(1-3/2\ S)\ \sin 2\theta$$

and replace in them $2E_0 \cos 2\theta$ and $2E_0 \sin 2\theta$ by the respective daily means. Observing that the left hand sides can be equated with differences of monthly means, X(Q-QM) and Z(Q-QM), we obtain by comparison with (7)

$$q_X = 1/(1+S) \text{ and } q_Z = 1/(1-1.5\cdot S) \qquad (9)$$

as now universal constants for the assumed source geometry and time dependence.

Assuming a penetration depth of Sq variations of C = 600 km gives with n = 2 in (4) a potential ratio of

$$S = 2/3\ \cdot\ (R-3C)/(R+2C) = 0.40,$$

and thereby as universal constants $q_X = 0.71$ and $q_Z = 2.5$.

5. Absolute Ring Current Measurements with MAGSAT Data - a Test of the FORBUSH Relation

The magnetic satellite mission MAGSAT verified most strikingly the existence of a substantial ring current in times of no magnetic activity. It enabled Langel and Estes (1985) to determine for the first time the absolute strength of the ring current, averaged over the time of the mission from November 1979 to May 1980. They arranged satellite magnetic vector data according to Sugiura's Dst index into nine groups and performed within each group a spherical harmonic analysis. The expansions were carried out to a maximum degree n = 13. For n = 1 external and internal potential coefficients were derived, for n = 2, 3, ... only internal coefficients. Thus, each analysis involved $(13+1)^2 - 1 = 168$ potential coefficients for the internal field and 3 potential coefficients for an external uniform ring current field.

Let q_1^0 denote the resulting external coefficient for the spherical harmonic P_1^0 and thus for a uniform ring current field parallel to the axis of rotation. Langel and Estes found a clear linear relationship between q_1^0 and the Dst index as a measure for relative ring current fluctuations, derived from ground observations. The regression line does not pass through the origin which implies the existence of a ring current field, when the Dst index is zero.

Langel and Estes have repeated their analysis several times in different versions, but with no significant changes in the slope or axis intercept of the regression line. They quote as their preferred determinations

$$q_1^0 = 18.62 - 0.63\ \mathrm{Dst}\ (\mathrm{nT})$$

for dawn segments and

$$q_1^0 = 20.30 - 0.68\ \mathrm{Dst}\ (\mathrm{nT})$$

for dusk segments of the selected orbits.

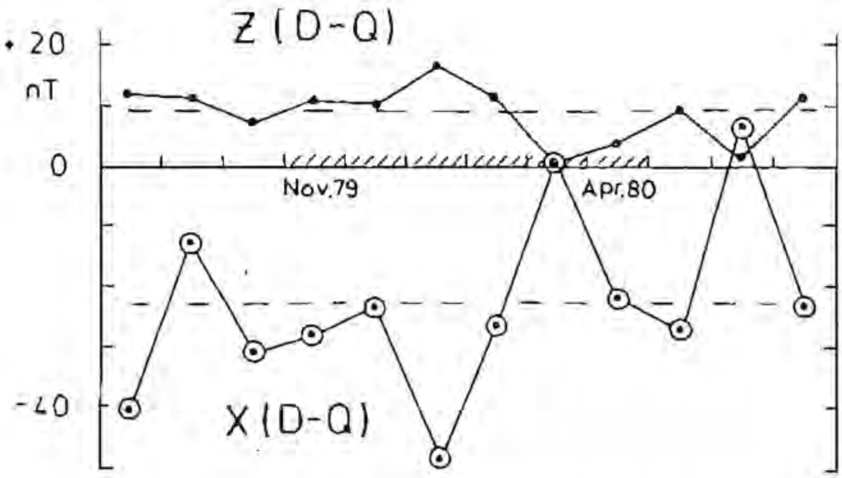

Fig. 9
Fuerstenfeldbruck differences of monthly means for D-days and Q-days during the MAGSAT mission 1979 - 80.

I shall try now to reproduce their results by evaluating the Forbush relation (1) with monthly means of Fuerstenfeldbruck. Fig. 9 shows the relevant differences of monthly means during the time of the MAGSAT mission. Their averages from November 1979 to April 80 - the most likely timespan to which Langel and Estes' regression analysis refers - are

$$X(D-Q) = -25.08\ \mathrm{nT},\quad Z(D-Q) = +9.08\ \mathrm{nT}.$$

The Z:X ratio for a uniform external source field, parallel to the rotation axis, and a penetration depth C_2 for the Dst recovery phase is

$$Z_{RC} : X_{RC} = -2C_2/R \cdot \tan\phi$$

at latitude ϕ as seen from (2) with (4). Inserting X(D-Q) and Z(D-Q) from above and ϕ = 48.17°N for Fuerstenfeldbruck gives

$$C_2 = 1030 \text{ km}.$$

The evaluation of the Forbush relation (1) with k/(1-k) = 0.68 yields

$$X_{RC}(Q) = 0.68 \cdot X(D-Q) = -17.1 \text{ nT}$$

for the quiet time ring current field, as seen from Fuerstenfeldbruck during the MAGSAT mission.

To obtain the external portion, $X_{RC}(Q)$ has to be divided by $(1+S_2)$, where S_2 is again the potential ratio of internal to external parts. Eq. (4) leads with n = 1 and the penetration depth C_2 from above to

$$S_2 = 1/2 \cdot (R-2C_2)/(R+C_2) = 0.29.$$

A final divison by cosϕ gives the equator value of the external ring current field which is identical with the external potential coefficient $q_1{}^0$ except for the sign.

In summary the Forbush relation, applied to the Fuerstenfeldbruck data, yields for the ring current on quiet days

$$q_1{}^0 = -(X_{RC}(Q))/(\cos\phi \cdot (1+S)) = 19.8 \text{ nT}.$$

This is in excellent agreement with Langel and Estes' determination from satellite data for times when the Dst index equals zero.

6. A Global Analysis of Monthly Means 1964 - 65

In the preceding sections, because data from a single observatory were involved, the global structure of Dst and Sq contributions to monthly means had to be approximated by just <u>one</u> spherical surface harmonic. Now I shall conduct for a 2-year interval a full-scale global analysis with data from 90 observatories: 72 in the northern hemisphere (Europe 27, Africa 4, America 11, Asia 20) and 18 in the southern hemisphere. The analysis is based on digitized yearbook tables of hourly means from January 1964 to December 1965.

In order to have a sufficiently smooth spatial dependence for a spherical harmonic analysis, observations too close to ionospheric jet currents are not included. Hence, the observatories selected from Dr. Winch's collection have a dip latitude of at least 6 degrees, to avoid the equatorial electrojet enhancement, and a geomagnetic latitude of not more than 60 degrees, to be sufficiently far from the auroral zones and polar electrojets.

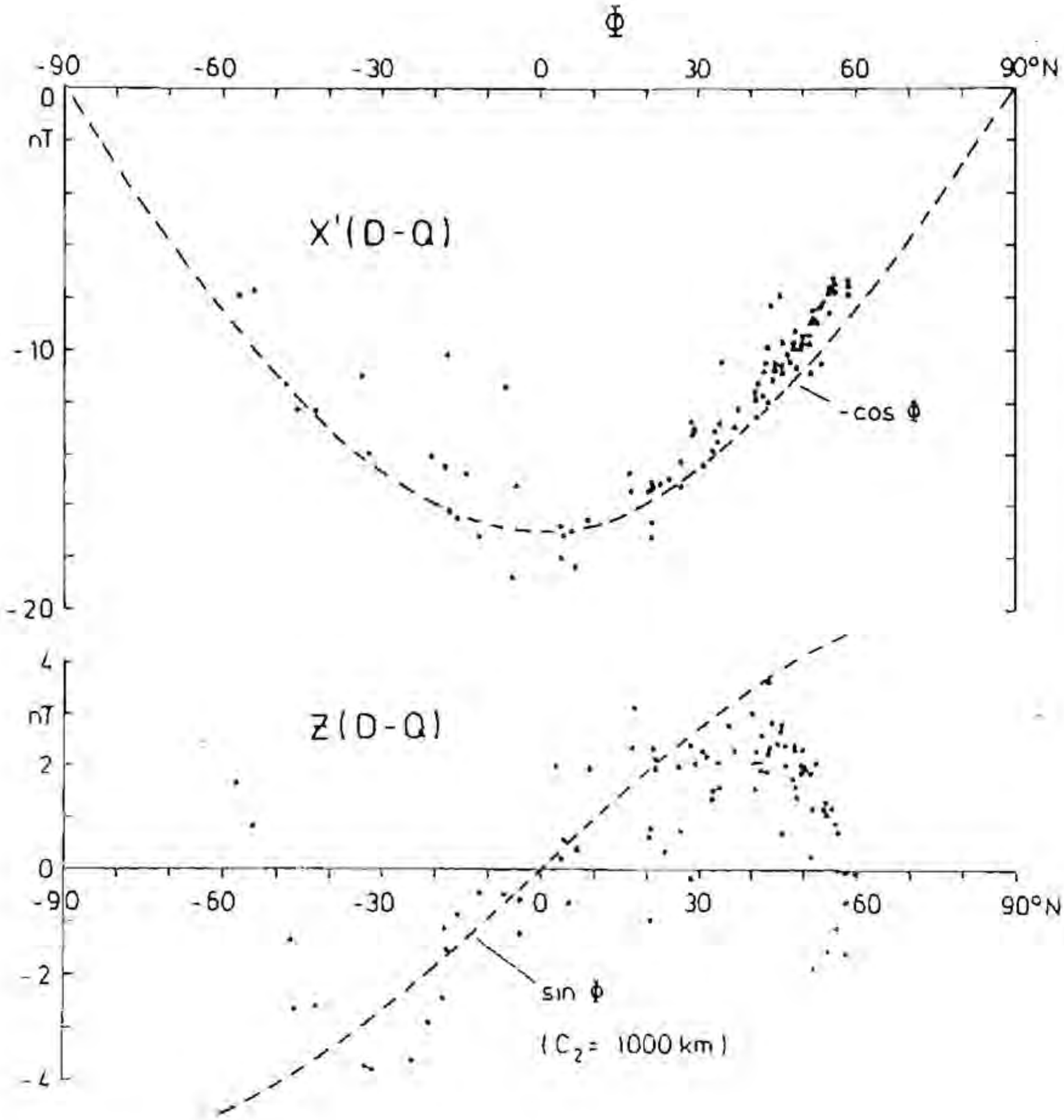

Fig. 10
Mean differences between D-day and Q-day daily means 1964 - 65, plotted against geomagnetic latitude for 90 observatories. Dashed curves indicate latitude dependences for an external ring current source with a penetration depth of 1000 km.

From the hourly values daily means and midnight values are derived and averaged over the month. This is done again separately for D-days and Q-days and with the described corrections for non-cyclic change. The midnight values are averages over three sequential hourly values at night. Their choice is such that the interval for the second hourly value coincides as much as possible with the local time interval from 1:30 to 2:30.

If, for instance, the longitude of a site is 50°E and therefore 2 hour local time corresponding to 22:40 Greenwich time, then the last three hourly values of the respective Greenwich day are averaged. If the first or third hourly value refer to hours outside this day, then either the last value of the preceding day is taken (as for 20°E) or the first value of the following day (as for 35°E).

I begin with ring current contributions to monthly means and consider the difference of monthly means for D-days and Q-days. According to Forbush's hypothesis (1), this difference measures the absolute strength of the ring current during the quiet days of the month. Since the ring current source geometry should not change greatly within the year, I use overall means for the two years.

In Fig. 10 the results for the 90 observatories are shown in dependence of geomagnetic latitude Φ. If the ring current field were uniform and downward at the geomagnetic pole on the northern hemisphere, then X'(D-Q) in geomagnetic coordinates would have the latitude dependence $-\cos\Phi$ and Z(D-Q) would vary as $+\sin\Phi$, as seen from (2). The data points in Fig. 10 follow this prediction and a spherical harmonic analysis has confirmed the dominance of the P_1^0-term over all others. The amplitudes of the dashed prediction curves has been fitted by eye in the case of X' and then calculated for Z, assuming a penetration depth C_2 = 1000 km for the Dst recovery phase. Eq. (2) with (4) defines the Z:X' amplitude ratio to be $2C_2/R = 0.31$ which agrees with the observations.

Thus, the assumptions on source geometry and Earth conductivity are both acceptable, but the variability of the Dst contributions is too small within the data sample to look for a correlation with solar activity. If similar global data were available for years of stronger solar activity, then a new test of Forbush's hypothesis could be conducted together with a determination of the penetration depth C_1 of Dst-related solare cycle variations.

Beyond 50 degrees geomagnetic latitude systematic deviations from the prediction occur, most notably in Z. They are positive close to the southern auroral zone and negative in the north, as if here in the daily average a westward polar jet would lower Z on D-days relative to Z on Q-days. This agrees with the observation that in the statistical average on the northern hemisphere westward polar jets after midnight are more intense than eastwards polar jets before midnight. On the southern hemisphere the current flows are reversed. Hence, the deviations can be understood.

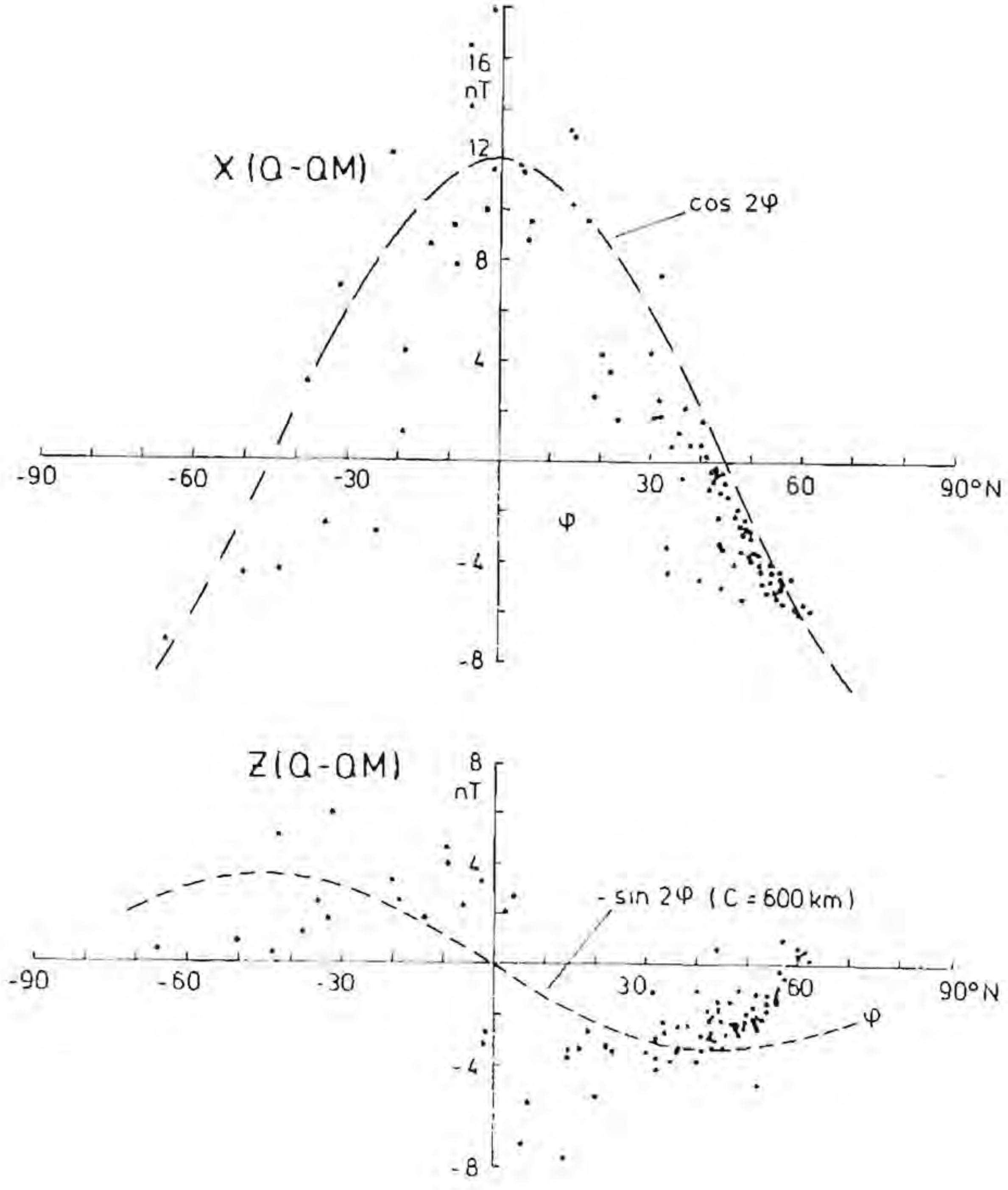

Fig. 11
E-months mean differences between daily means and midnight values on Q-days 1964 - 65, plotted against geographic latitude for 90 observatories. Dashed curves indicate latitude dependence for a P_2^1 Sq-source with a penetration depth of 600 km.

In the global analysis of Sq contributions to monthly means a strong seasonal dependece is to be expected and the months are grouped according to their Lloyd seasons into

E-months = March - April, September - October,
D-months = November - February,
J-months = May - August.

As shown in Section 4, Sq contributions are best identified by the difference of daily means and midnight values on quiet days.

Fig. 11 shows the resulting mean differences X(Q-QM) and Z(Q-QM) for the eight E-months, plotted against geographic latitude ϕ. During E-months Sq currents are mirror-symmetric with respect to the equator and the Sq potential, when developped into a series of spherical harmonics, contains only spherical terms with an uneven difference between degree n and order m, i.e. for $m \neq 0$ with an uneven number of zeroes between poles. The dashed curves in Fig. 11 refer to the one-term source presentation from Section 4 by P_2^1, yielding a $+\cos 2\phi$ prediction curve for X and a $-\sin 2\phi$ prediction curve for Z (cf. Eqs. 8). Again a preconceived amplitude ratio Z:X of $3C/R = 0.28$ is used with $C = 600$ km as assumed penetration depth for Sq variations.

We observe for X(Q-QM) the expected latitude dependence: Positive peakvalues near to the equator and a reversal of sign in midlatitudes. There is, however, a systematic deviation from the predicted zero at 45 degrees. It indicates that the source potential should be approximated by a combination of at least two spherical harmonics, say P_2^1 and P_3^2. Their derivatives with respect to co-latitude pass through zero at 45 and 35.3 degrees, respectively, which would shift the combined zero of X(Q-QM) from 45 degrees toward lower latitudes as it is required by the data.

In Z no clear latitude dependence evolves except that Z(Q-QM) is mostly negative on the northern hemisphere and mostly positive on the southern hemisphere. The large scatter reflects the smallness of Sq variations during the studied years of minimum solar activity, not counting the fact that induction reduces the Z amplitude to a fraction of the X amplitude.

In any case, the global presentations in Fig. 10 and 11 demonstrate most clearly the great difference in the source geometry of Dst and Sq contributions to monthly and thereby annual means. Even though only years of minimum solar activity were involved, the same difference should distinguish Dst-related and Sq-related parts of solar cycle variations.

I conclude this section with a separation analysis of the Sq-related differences X(Q-QM), Y(Q-QM), Z(Q-QM). Combining (6) with (7) in Section 4, we write for the external parts, which are identical with the daily means of Sq variations:

$$
\begin{aligned}
X(Q-QM)_{ext} &= \langle X_{SQ} \rangle = q_X \; X(Q-QM), \\
Y(Q-QM)_{ext} &= \langle Y_{SQ} \rangle = q_Y \; Y(Q-QM), \qquad (10) \\
Z(Q-QM)_{ext} &= \langle Z_{SQ} \rangle = q_Z \; Z(Q-QM).
\end{aligned}
$$

It is presumed that no Sq variations of external origin exist at local midnight.

The thus introduced q-factors are local constants for a given source geometry and Earth model of conductivity. However, if a one-term source approximation is used, they are universal constants as shown in Section 4. It is the purpose of the separation to determine the q-factors in (10) individually without any assumptions about source geometry and Earth conductivity.

The separation analysis is done with spherical harmonics. A first series approximates month by month in a least squares sense X(Q-QM) and Y(Q-QM) at the 90 locations as derivatives of a potential U(Q-QM), a second series approximates Z(Q-QM). By combining the expansion coefficients of the two series, the potential coefficients can be separated into parts of external and internal origin, and by synthesis field components from either external or internal sources are found.

I have used in each series 3 zonal terms with the spherical harmonic P_n^0 (n = 1, 2, 3) and 32 non-zonal terms with $P_n^m \cos m\lambda$ and $P_n^m \sin m\lambda$ (m = 1, 2, 3, 4 and n = m, m+1, m+2, m+3), where λ denotes longitude.

The results of the global separation analysis are presented as follows: For selected observatories the external parts of differences are plotted month by month against the sums of external and internal parts which approximate as "synthetic" values the observed differences. In the same way seasonal and all-year means are displayed. Each data point defines the q-factor for a given month and location.

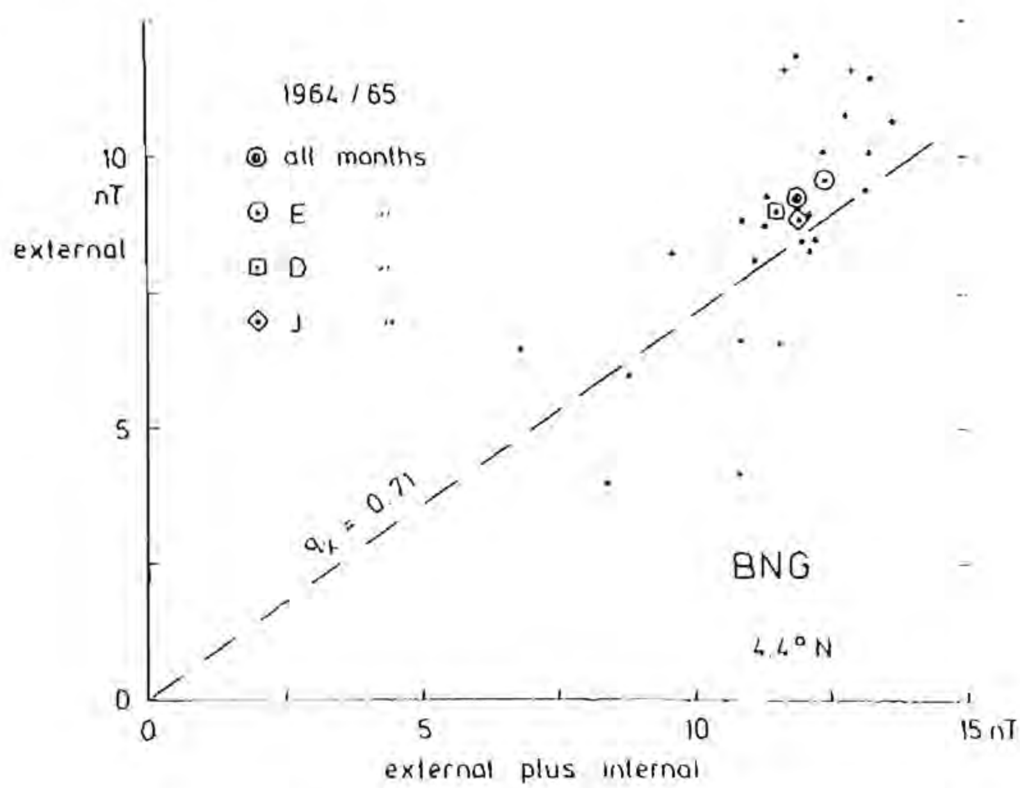

Fig. 12
Monthly and seasonal mean differences between daily means and midnight values 1964 - 65. Shown are the external parts of these differences in X for the low-latitude observatory Bangui, as obtained from a global analysis, versus their synthetic sums of external and internal parts. The dashed line refers to a q_x-factor of 0.71, derived for a P_2^1 Sq-source and a penetration depth of 600 km.

In Fig. 12 the selected observatory is Bangui in Central Africa, where the Sq variations are strongest in X. Thus, $X(Q-QM)_{ext}$ is plotted against X(Q-QM). Even though the seasonal variability is small, a nearly constant ratio can be observed. Moreover, the data points are close to the dashed line for the predicted q-factor q_X = 0.71 from Section 4.

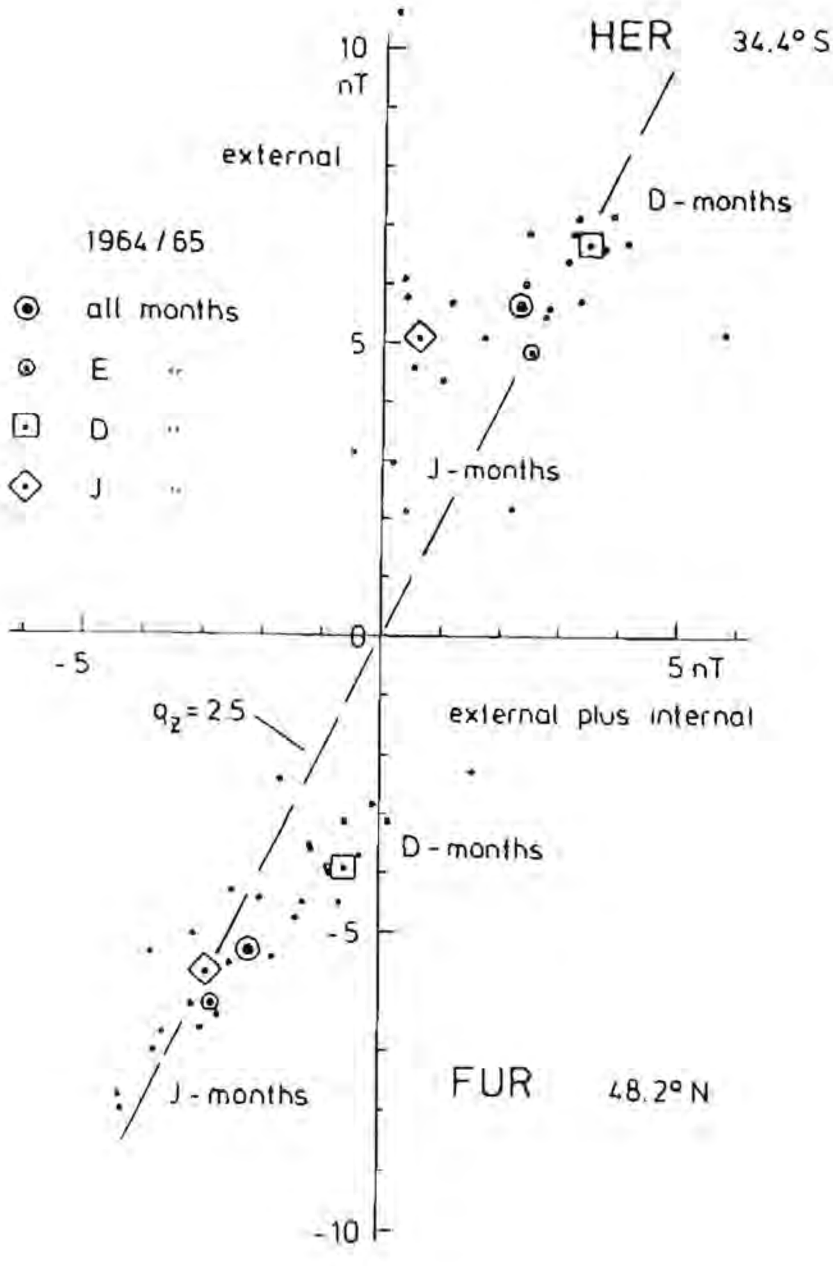

Fig. 13
Same as in Fig. 12 for Z at two mid-latitude observatories with a predicted q_Z-factor of 2.5.

In Fig. 13 the selected observatories lie in midlatitudes: Hermanus on the southern hemisphere and Fuerstenfeldbruck on the northern hemisphere. Both observatories are close to the centers of the respective hemispherical Sq current loops and thus should have large Z-variations with opposite signs. The resulting daily mean, when measured against true zero, should be positive at Hermanus and negative at Fuerstenfeldbruck.

This is indeed observed, but now with a strong seasonal variability, as to be expected. If we ignore the weak Sq variations during the respective winter months, a stable q_Z-ratio evolves which coincides well with the predicted value $q_Z = 2.5$. Note that the observed differences Z(Q-QM) are only small fractions of their external parts which exemplifies the important role of internal induction.

In summary, at locations where Sq variations are strong, the simplying assumptions from Section 4 about source structure and induction effects hold and the global analysis yields the predicted q-factors. However, the assumptions are not adequate, where the Sq variations are weak, say, for variations in X at an midlatitude observatory. It has been pointed out already that Fuerstenfeldbruck has a clearly negative difference X(Q-QM), whereas the one-term source model would predict it to be close to zero. At such places the global separation analysis can yield more suitable local q-factors to reconstruct daily means in Sq from observed differences of daily means and midnight values.

Fig. 14 demonstrates their determination for Fuerstenfeldbruck. Ignoring D-months we infer from this plot of seasonal means the following local q-factors:

$$q_X = 1.0,\ q_Y = 0.5,\ q_Z = 2.5.$$

For X the internal part obviously just passes through zero, implying that contributions from more than one spherical harmonic cancel each other. For Z the universal q-factor for a one-term source presentation is reproduced, while for q_Y no explanation can be given. However, consistent results are obtained for all seasons which leaves little doubt that the daily means in Y are not on the local midnight level.

7. Corrected Annual Means 1951 - 1968

The annual means in question are the averaged daily means of Q-days. They are combined with the corresponding annual means for D-days and midnight values on Q-days to define Dst and Sq corrections with the methods of Sections 3 and 4. Note that the notations X(Q), X(D), X(QM),.... refer in this section to annual rather than monthly means. The seasonal dependence, notably in Sq, is ignored. The results are presented numerically in the following three tabulations for X, Y, and Z. All entries are in nanotesla and refer to the local observatory standard of Fuerstenfeldbruck. Add -12 nT for X, +6 nT for Y, and -25 nT for Z to obtain the "International Magnetic Standard".

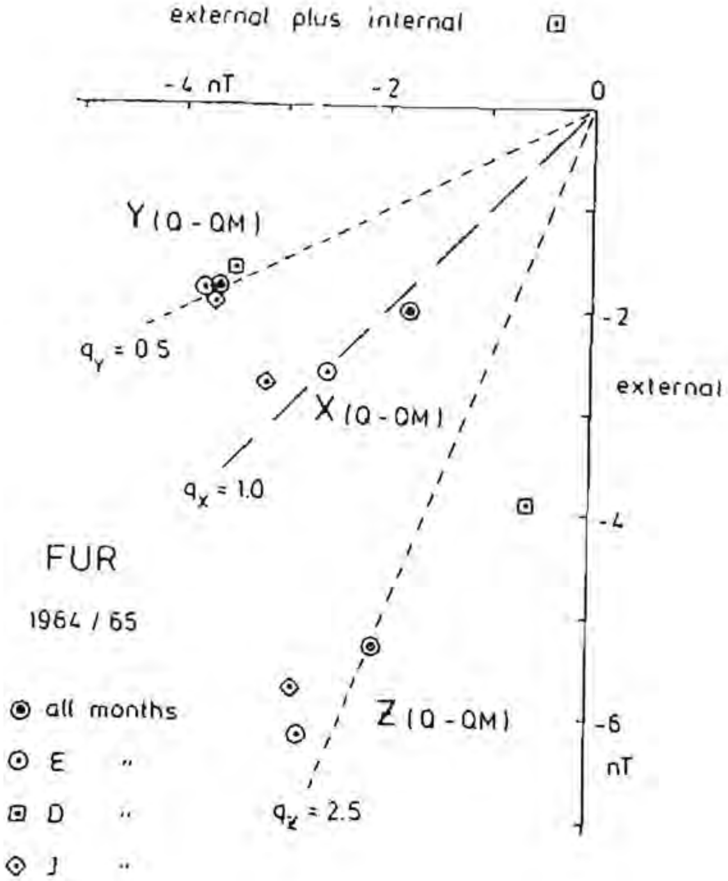

Fig. 14
Same as in Fig. 12, but for seasonal means in <u>all</u> components to determine local q-factors for Fuerstenfeldbruck.

For completeness the tables begin in the first column with annual means of all days. They are identical with the published annual values in the yearbooks except for occasional discrepancies of 1 nT, presumably arising from accumulated round-off errors. The next three entries are the annual mean of Q-days, the annual mean difference between D- and Q-day daily means, and the annual mean difference between daily mean and midnight value on Q-days. Then follow the calculated quiet day contributions from the ring current and Sq. Here $X_{SQ}(Q)$, ... stand for the averaged daily means $\langle X_{SQ} \rangle$, ... of quiet days, as defined in Section 4.

The derivation of the ring current field is performed in geomagnetic coordinates, inserting into the Forbush relation (5) $X'(D-Q) = \cos D_0 \cdot X(D-Q) + \sin D_0 \cdot Y(D-Q)$ with D_0 as angle between the geomagnetic and geographic meridian. At Fuerstenfeldbruck $D_0 = -17.0°$. The resulting horizontal ring current field X'_{RC} is projected back onto geographic directions. Hence, the Forbush relations to find the ring current field are

$$\begin{aligned} X_{RC} &= k/(1-k) \cdot \{c^2 \cdot X(D-Q) + cs \cdot Y(D-Q)\} \\ Y_{RC} &= k/(1-k) \cdot \{s^2 \cdot Y(D-Q) + cs \cdot X(D-Q)\} \\ Z_{RC} &= k/(1-k) \cdot \beta \cdot Z(D-Q) \end{aligned} \qquad (11)$$

with $c = \cos D_0$, $s = \sin D_0$ and $\beta = C_1/C_2$.

	X(A)	X(Q)	X(D-Q)	X(Q-QM)	$X_{RC}(Q)$	$X_{SQ}(Q)$	X*
1951	20307	20318.6	-26.2	0.1	-13.5	0.1	20332
1952	322	333.2	-25.1	0.0	-12.2	0.0	345
1953	340	348.9	-23.2	-0.2	-12.0	-0.2	361
1954	359	364.4	-12.3	-0.3	- 6.2	-0.3	371
1955	366	374.0	-22.7	-0.3	-11.5	-0.3	386
1956	368	382.3	-38.5	-1.8	-19.4	-1.8	403
1957	380	394.8	-44.9	-1.3	-22.4	-1.3	419
1958	398	412.1	-45.0	-3.8	-22.5	-3.8	438
1959	409	425.5	-47.8	-1.0	-23.8	-1.0	450
1960	422	438.2	-41.9	-1.2	-21.0	-1.2	460
1961	448	458.3	-31.8	-1.0	-16.0	-1.0	475
1962	472	479.5	-18.5	-0.5	- 9.1	-0.5	489
1963	487	495.3	-20.3	0.5	- 9.9	0.5	505
1964	506	511.7	-12.5	0.4	- 6.5	0.4	518
1965	526	529.0	-12.9	0.0	- 6.5	0.0	535
1966	538	545.7	-22.8	0.2	-11.5	0.2	557
1967	551	560.8	-28.1	-0.9	-14.4	-0.9	576
1968	572	581.8	-26.5	-1.9	-13.1	-1.9	597

	Y(A)	Y(Q)	Y(D-Q)	Y(Q-QM)	$Y_{RC}(Q)$	$Y_{SQ}(Q)$	Y*
1951	-1180	-1184.7	11.2	-6.5	4.2	-3.3	-1186
1952	-1141	-1144.9	5.2	-5.9	3.7	-3.0	-1146
1953	-1105	-1108.3	9.7	-4.7	3.7	-2.3	-1110
1954	-1068	-1069.9	4.1	-5.4	1.9	-2.7	-1069
1955	-1031	-1033.3	8.3	-4.2	3.5	-2.1	-1035
1956	- 994	- 998.5	13.1	-4.8	6.0	-2.4	-1002
1957	- 966	- 970.3	13.6	-7.7	6.9	-3.9	- 973
1958	- 937	- 942.1	13.4	-7.1	6.9	-3.6	- 945
1959	- 908	- 912.6	13.5	-6.7	7.3	-3.3	- 917
1960	- 880	- 885.4	12.8	-4.8	6.4	-2.4	- 889
1961	- 854	- 857.8	10.1	-4.9	4.9	-2.4	- 860
1962	- 827	- 828.2	4.6	-3.8	2.8	-1.9	- 829
1963	- 802	- 802.8	4.9	-3.9	3.0	-1.9	- 804
1964	- 778	- 779.0	5.5	-3.5	2.0	-1.7	- 779
1965	- 758	- 758.7	4.0	-3.7	2.0	-1.9	- 759
1966	- 736	- 738.5	7.5	-4.5	3.5	-2.2	- 740
1967	- 717	- 718.9	11.2	-4.6	4.4	-2.3	- 721
1968	- 701	- 702.7	7.3	-4.9	4.0	-2.5	- 704

	Z(A)	Z(Q)	Z(D-Q)	Z(Q-QM)	$Z_{RC}(Q)$	$Z_{SQ}(Q)$	Z*
1951	41822	41818.5	8.0	-2.7	12.7	- 6.7	41812
1952	841	837.7	6.5	-2.6	10.3	- 6.5	834
1953	857	853.4	6.5	-2.4	10.4	- 6.0	849
1954	883	880.6	4.5	-2.0	7.2	- 5.0	879
1955	905	902.5	5.5	-2.5	8.8	- 6.3	900
1956	953	946.7	13.6	-3.7	21.7	- 9.2	934
1957	979	972.1	15.1	-5.8	24.1	-14.6	963
1958	42006	42000.0	15.8	-4.3	25.2	-10.8	986
1959	027	020.3	18.2	-4.9	28.9	-12.3	42004
1960	057	049.4	18.7	-4.6	29.7	-11.5	031
1961	072	068.5	10.2	-3.3	16.2	- 8.3	061
1962	089	086.5	5.4	-2.0	8.6	- 5.0	083
1963	109	105.7	6.8	-2.4	10.8	- 6.0	101
1964	123	120.8	3.8	-2.1	6.0	- 5.2	120
1965	134	133.2	3.9	-1.9	6.2	- 4.8	132
1966	154	151.1	7.4	-3.2	11.8	- 7.9	147
1967	175	172.7	8.8	-2.8	14.0	- 7.1	166
1968	196	193.2	9.9	-3.2	15.7	- 7.9	185

Forbush's original estimate $k/(1-k) = 0.68$ has been replaced by 0.5 because it produced oscillating corrected means X* opposite to the solar cycle variations of X(Q). No significant internal induction has been found for the 11-year period variation, yielding $C_1 = R/2 = 3186$ km and $\beta = C_1/C_2 = 3.186$ with $C_2 = 1000$ km. Eq. (7) for the Sq contributions are evaluated with the q-factors from the global separation analysis as quoted at the end of Section 6.

With regard to the presumed ring current origin of the differences of D- and Q-days, note that in all years Y(D-Q) is positive and X(D-Q) negative with an overall ratio of 8.7/-27.8 = -0.31. For a ring current source in the equatorial plane of geomagnetic coordinates this ratio should be tan D_0. The resulting angle $D_0 = -17.4°$ is in excellent agreement with the above cited value for Fuerstenfeldbruck. In addition, Z(X-Q) is positive with an overall ratio to X'(D-Q) of 9.4/-29.2 = -0.33. Insertion into (2) with (4) for the penetration depth, $Z = 2\ C_2/R \cdot \tan\Phi \cdot X'$, yields with $\Phi = 48.6°$ for Fuerstenfeldbruck $C_2 = 905$ km which is an acceptable penetration depth for the Dst recovery phase of magnetic storms.

The last entries in the tabulations are the corrected annual values

$$X^* = X(Q) - X_{RC}(Q) - X_{SQ}(Q) \qquad (12)$$
$$Y^* = \ldots\ldots, \quad Z^* =$$

for the true level of the undisturbed Earth's magnetic field, freed from all external effects and internal effects by induction. They are shown in Fig. 15 together with the uncorrected annual means of quiet days. A linear trend with a best fitting slope as indicated has been subtracted, but only to achieve a convenient visual display with no bearing on the here performed analysis of solar cycle variations.

Beginning in Fig. 15 with the northcomponent X, a sharp drop of the uncorrected annual means X(Q) occurs, when solar activity starts to increase after passing through the 1954 sunspot minimum. This ring current effect disappears three years after the 1958 sunspot maximum and X(Q) returns slowly to the level which a constant secular variation predicts from the foregoing sunspot minimum.

In contrast, the corrected annual means X* pass more or less smoothly through the solar cycle. From 1951 onward the thus revealed secular variations decrease until 1964 where a sudden acceleration sets in which can be followed up until 1968.

Occasional irregular oscillations should not be surprising because the corrections for ring current effects involve the use of the highly unstable monthly means of D-days (cf. Fig. 3). In fact, only these Dst effects matter at a mid-latitude observatory where the Sq-related corrections in X are relatively small.

This is different for the eastcomponent Y, where the Sq and Dst corrections are comparable in size, but opposite in sign. Hence, the uncorrected and corrected annual means lie close together. The dominant feature is the continuous slow-down of the secular variations throughout the entire time interval which clearly is of genuine internal origin.

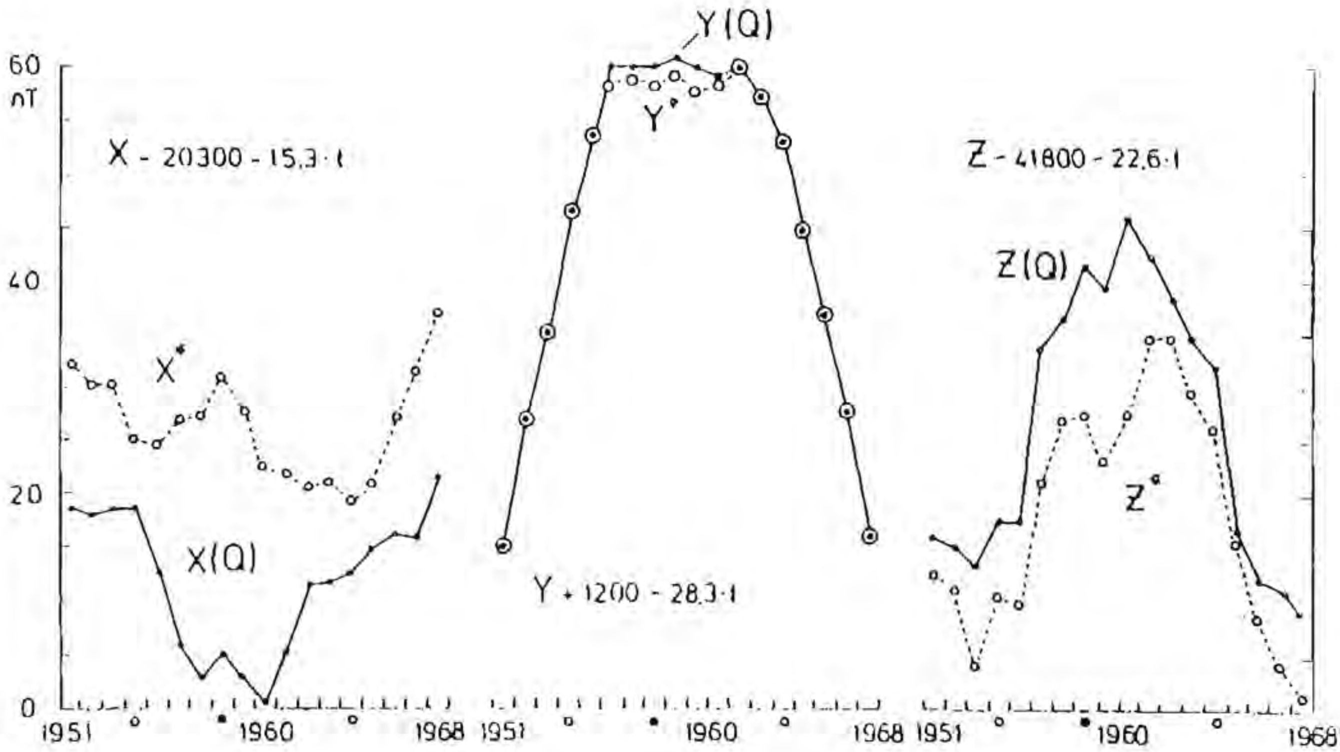

Fig. 15
Corrected and uncorrected annual means of Q-days at Fuerstenfeldbruck 1951 - 1968; t: time in years after 1951. See tables and comments on them in Sec. 7.

The same applies to Z, where also Dst and Sq corrections are opposed, even though those for Dst dominate. The resulting combined correction, however, can compensate only to some extent the 30 nT increase of Z(Q) between 1956 and 1963 relative to the predicted level for a constant secular variation. Except for the sharp increase from 1955 to 1956, which is at least partially due to the increase of solar activity, this seems to be also a genuine internal effect, implying a temporary acceleration of the secular variation with a subsequent slow-down from 1964 onwards.

With regard to the absolute level of the main field, the effect of a constant ring current on annual means is note-worthy. In X the annual means of quiet days lie, as to be expected for a westward ring current, consistently below the calculated true zero reference level X*. If annual means of all days were used, the distance to X* would be even greater. For X(Q) this offset amounts to 6 nT in years of minimum sunspot number, but increases to more than 20 nT in years of maximum sunspot number. In Z the offsets are of the same size, but opposite in sign. Thus, a background 7 nT external ring current field seems to exist even at times of minimum solar activity. See Section 5 for the performed calculation.

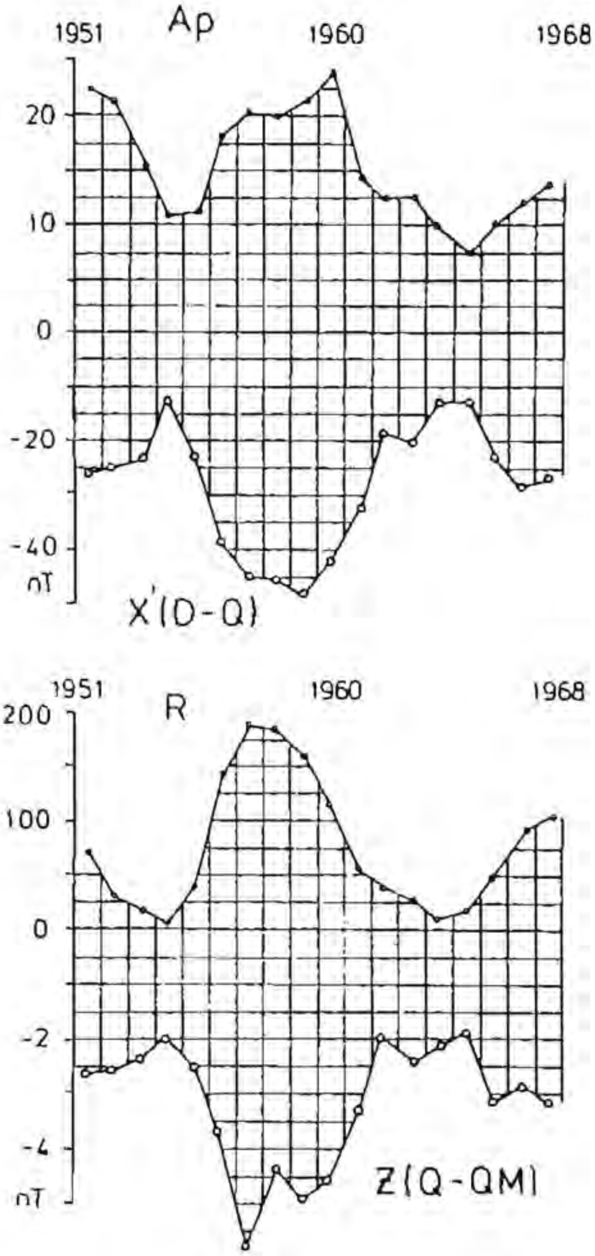

Fig. 16
Sq and Dst external effects on annual means at Fuerstenfeldbruck 1951 - 68, shown in dependence of the sunspot number R and magnetic activity index Ap, respectively.

Finally I shall investigate, how well the external effects correlate with solar radiation data. These are for the relevant years the annual means of the Definite Sunspot-Numbers R (derived by the Eidgenössische Sternwarte Zürich, M. Waldmeier) and of the Equivalent Planetary Amplitude Ap for magnetic activity (taken from the IAGA Bulletins No. 12f to w1):

	1951	52	53	54	55	56	57	58	59
R	69.4	31.4	13.9	4.4	38.0	141.7	190.2	184.8	159.0
Ap	22.3	21.2	15.7	11.0	11.3	18.0	20.1	19.2	21.3

	1960	61	62	63	64	65	66	67	68
R	112.3	53.9	37.5	27.9	10.2	15.1	47.0	93.8	105.9
Ap	23.6	14.4	12.3	12.6	9.9	7.7	10.2	12.0	13.5

It is well known that during the solar cycle the "mean daily inequality" (i.e. the deviations of hourly values from the daily mean, averaged without regard to sign over the day) as a measure for the Sq amplitude follows closely the changing sunspot number as a measure for solar wave radiation (cf. Chapman and Bartels, 1940; Section 7.3). Since in mid-latitudes the strongest Sq effect on annual means is in Z, I compare in Fig. 16 Z(Q-QM) as a measure for the daily mean of Sq with R. Similarly, ring current effects should follow the changing particle radiation from the sun as expressed by the changing level of magnetic activity. Hence, in the same figure X'(D-Q) as a measure for the absolute strength of the ring current is plotted against Ap. Since the maximum of magnetic activity in 1960 is characteristically delayed by three years against the sunspot maximum, wave and particle effects can be distinguished. Fig. 16 confirms the proposed correlations.

8. Conclusions

This study presents a novel approach to separate solar cycle variations from secular variations of genuine internal origin, without the usual resort to a polynomial fit for sequences of annual means and with data from only one observatory. Instead, three types of monthly means are derived which average either the daily means of quiet days or those of disturbed days or the midnight values of quiet days. All display the 11-year period variation of the solar cycle, those from midnight values in addition strong annual variations which are associated with Sq and presumably of exclusively internal origin.

Dst-related contributions to monthly and annual means of quiet days are derived with Forbush-relations which connect the absolute strength of the mean ring current field to the difference of D- and Q-day monthly means. Similarly the absolute strength of the Sq field is derived from the difference between the daily means and the midnight values of quiet days. The basic correctness of the underlying assumptions has been confirmed with satellite data during the MAGSAT mission and with a global analysis, involving data from 90 observatories. The global analysis reveals also the expected and distinctly different source field structures of Dst- and Sq-related external effects.

The ratios of vertical to horizontal fields, as expressed by the cited differences of monthly means, are consistent with penetration depths of 1000 km for the Dst recovery phase of magnetic storms and 600 km for Sq. These values are equivalent to potential ratios of internal to external parts of 0.29 (n=1) and 0.40 (n=2), respectively. No significant internal part by induction could be found, however, for the 11-year period of Dst- or Sq-related parts of solar cycle variations.

Finally, annual means of the ring current and Sq fields are derived and subtracted from the observed annual means of quiet days. This identifies the true zero level of the undisturbed Earth's magnetic field at Fuerstenfeldbruck and reveals its secular change during the investigated timespan from 1951 to 1968. The Sq-corrections for annual means correlate well with annual means of sunspot numbers R, the Dst-corrections with annual means of equivalent planetary amplitudes Ap.

Since 150 years magnetic observatories in many countries collect the fundamental data for our understanding of the Earth's magnetism. Their reports and yearbooks contain a wealth of still only partially exploited information and with this study I wish to pay tribute to the outstanding service of the observatory Fuerstenfeldbruck.

References

A.A. Ashour and A.T. Price: Night-Time Earth Currents Associated with the Daily Magnetic Variations Geophys. J. 10, 1 - 15, (1965)

S. Chapman and J. Bartels: Geomagnetism (2 volumes), Oxford University Press, 1049 pp. (1940).

J. Ducruix, V. Courtillot, J.-L. Le Mouël: The late 1960s secular variation impulse, the eleven year magnetic variation and the electrical conductivity of the deep mantle. Geophys. J. R. Astron. Soc. 61, 73- (1980).

S.E. Forbush and L. Beach: The absolute geomagnetic field of the equatorial ring current. Carnegie Institution Yearbook 65, 28 - 36, (1967).

A. Grafe: Die Bedeutung der Abweichungen geomagnetischer Tagesmittel vom sogenannten Normalwert für die Analyse des geomagnetischen Ringstromeffektes. Dt. Akad. Wiss. Berlin, Abh. 31 des Geomagn. Instituts Potsdam (1964).

A.M. Isikara: Solar cycle controlled variation of the geomagnetic field. Acta Geodaet. et Montanist. Acad. Sci. Hung. Tomus 12, 397-405 (1977).

R.A. Langel and R.H. Estes: Large-scale, near-field magnetic fields from external sources and the corresponding induced internal field. J. Geophy. Res. 90, 2487 - 2494 (1985).

D. Voppel: On the external part of the geomagnetic secular variations of D and H at Wingst observatory. Dt. hydrogr. Z. 35, 169-176, (1982).

T. Yukutake: The solar cycle contribution to the secular change in the geomagnetic field. Geomagn. Geoelectr. 17, 287-309 (1965).

T. Yukutake and J.C. Cain: Solar cycle variations of the first-degree spherical harmonic components of the geomagnetic field. J. Geomagn. Geoelectr. 31, 509-544 (1979).