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Application of solar quiet day (Sq) current in determining mantle electrical-depth conductivity structure – A review

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ABSTRACT

This study has extensively reviewed the application of solar quiet day (Sq) current variation in determining mantle electrical–depth conductivity structure, in a number of countries and various hemispheres. The review includes basic theories and methods of analysis. There are few recent works on the determination of mantle conductivity-depth structure using Sq current. Results obtained have yielded very interesting and exciting information, hence, the need for this review. This review is expected to throw more light to the understanding of effects of Sq on mantle conductivity. There is evidence of controversy and marked differences in conductivity variation in the mantle when different methods are applied, from available literature on the application of Sq on mantle electrical depth conductivity. Other methods applying 1-D, 2-D and 3-D were also reviewed and hence, we recommend the need of combining the above methods with Sq method in future work for more robust results. We have discovered that findings emanating from this work could lead to more understanding of application of Sq current in determining mantle electrical depth conductivity structure.

Contents

1. Introduction

One of the transient geomagnetic variations that are closely related to solar events and also to a number of other related phenomena of the upper atmosphere is the solar quiet daily variation (Sq). Sq as external part of geomagnetic variations is caused by electric currents which flow mainly in the dynamo region at heights of about 70–160 km. The part of the ionosphere where the current is produced is referred to as electromagnetic dynamo. Forbes (1981) observed that the history of ionospheric dynamo theory followed the development of atmospheric tidal theory as well as knowledge of ionospheric conductivities.

The geomagnetic variation is usually employed in estimating the conductivity within the outer region of the earth because the strength of the induced telluric currents depends on the distribution of electrical conductivity. The period of variation determines the depth to which the currents penetrate. Short period variations penetrate to shallow depths and vice versa for longer period variations. It is important to note that the depth of penetration of an oscillation of period T above a uniform half-space of conductivity σ is given as; $(T/4\pi^2\ \sigma)^{1/2}$. Hence, the entire spectrum of external

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geomagnetic events from period of 1 s to a year or more is very useful in probing the conductivity of the earth down to approximately 1000–1600 km depth.

Method employed is basically dependent on the possibility of separating the internal and external parts of the field by spherical harmonic analysis (SHA) or other methods. Bott (1982) ascertained that, by determining the relative amplitude and phase difference of both the internal and external components for the variation of a given period, it becomes imperative that estimation of the weighted mean value of the conductivity down to the depth of penetration of the currents is possible. Furthermore, he concluded that by performing this analysis at different period of variations, a rough conductivity-depth distribution could be estimated down to penetration depth, even for largest period variation available for the analysis. This is achieved by employing trial and error modeling or inversion.

To date, applying solar quiet day current in determining mantle electrical–depth conductivity structure has taken a new dimension and has contributed tremendously in mapping mantle conductivity. This is not without reasons; this has proved to be a very powerful tool in this area of research. More so, that the previously wide used methods-like magnetotelluric and geomagnetic deep sounding methods have failed to penetrate certain depth and could not produce result, particularly in West Africa, hence this becomes a very powerful and useful method.

Anomalies of electrical conductivity are quite helpful in identifying the zones of melting and dehydration. Thus, delineation of these zones is of acute importance in understanding the mobile areas of the Earth's crust and upper mantle, where tectonic movements and regional metamorphism lead to distinct patterns of subsurface conductivity (Chandrasekhar, 2011). Hence, areas of high conductivity within the crust close to the Earth's surface that corresponds to zones of melting and mobile areas may lead to ejection of sulphur dioxide (SO_2) into the atmosphere during volcanic eruption. Therefore, there is the possibility of release of volcanic sulphur dioxide (SO_2) into the strastosphere during volcanic eruption through this region which could contribute to climate change. However, more work need to be done before a definite conclusion can be drawn.

Many researchers have since, after Campbell et al. (1998), carried out extensive research works in other continents, hemispheres and countries, using Sq current in mapping the mantle conductivity.

This paper presents a review of relevant works in ionospheric currents of geomagnetic Sq current. The separation of both internal as well as external current will be used. The details of mapping mantle conductivity, using Sq current system will be critically reviewed. The results of different works in this area will be x-rayed in view of critically drawing some inferences and deducting benefits derived from them.

2. Theory

Knowledge of physical processes that give rise to quiet daily variations can reveal details of the deep Earth and upper atmosphere that are not easily obtained by any other means (Campbell, 1989). These recent methods need to be reviewed extensively. Geomagnetic application of the SHA technique was originated by Gauss in 1838. Using the technique, Schuster (1889, 1902) proved that the larger part of Sq was due to current sources external to the Earth and that the smaller part could arise from induction within the conducting Earth. The method of analysis involves the differential equations of Maxwell (1873), who showed that all the electromagnetic laws governing electric and magnetic field phenomena could be derived from a few compact mathematical expressions. For the situation in which field measurements are available about a spherical surface that separates the source from the induced currents (and current does not flow across this surface), Maxwell's equations were given a separable series solution in the spherical coordinates r, θ, and ϕ by Gauss (1838), in his spherical harmonic analysis (SHA). A solution for the earth's main field (Gauss, 1838) satisfying these requirements have the converging series of terms (Campbell, 2003);

$$V = a\sum_{n=1}^{\infty}\left[\left(\frac{r}{a}\right)^{n} S_n^e + \left(\frac{a}{r}\right)^{n+1} S_n^i\right] \tag{1}$$

where a is the Earth's radius, R_e. The series solution means that for each value of n, the electromagnetic laws are obeyed as if that term were the only contribution to the field.

From Equation (1), it is observed that there are two series; one with terms in r^n and the other with terms in $\left({}^{1}\!/_{r}\right)^n$. The terms in r^n become larger and larger as r increases, this implies that one must be approaching the current source of an external field in the increasing r direction. For the second series, the $\left({}^{1}\!/_{r}\right)^n$ terms become larger and larger as r becomes smaller and smaller, which means one must be approaching the current source of an internal field in the decreasing r direction. For the Sq analysis, such series represent a separation of the earth's magnetic potential function into the composite external and internal contributions of the geomagnetic field. The process allows the construction of the ionospheric dynamo current system and also the induced field gives information on the conductivity structure of the Earth.

When V is determined from measurements of the field about the Earth, analyses show that mostly all the contribution comes from the internal part of the potential function expansion. The magnetic potential of the Sq field measured from the daily mean values at universal time, T, from both the external source current and the internal (induced) current is expressed by;

$$\begin{aligned} V_n^m = C + a\sum_{n=1}^{\infty}\sum_{m=0}^{n}\Bigg\{&\left(a_n^{me}\left(\frac{r}{a}\right)^{n} + a_n^{mi}\left(\frac{a}{r}\right)^{n+1}\right)\cos(m\phi) \\ &+ \left(b_n^{me}\left(\frac{r}{a}\right)^{n} + b_n^{mi}\left(\frac{a}{r}\right)^{n+1}\right)\sin(m\phi)\Bigg\}P_n^m(\theta) \end{aligned} \tag{2}$$

where $C, \theta, a, r, and\ \phi$ denote a constant of integration, the geomagnetic colatitude, the geocentric distance, the Earth's radius and local time of the observatory respectively. The a_n^{me} , a_n^{mi}, b_n^{me} and b_n^{mi} are Legendre polynomial coefficients, where e and i represent the external and internal values respectively. $P_n^m(\theta)$ is Legendre polynomial function of colatitude θ only. They are quasi-sinusoidal oscillations having n-m+1 waves (or just n waves if m = 0) as θ changes from 0^0 to 360^0 along a great circle of longitude. Since Sq is cyclic in 24 h, there are no m = 0 terms. The integers, n and m, are called degree and order respectively, n has a value of 1 or greater and m is always ≤ n. In Sq analysis, $r \approx a(\ a =$ the Earth's radius, $R_e)$.

Taking $a_n^{me} + a_n^{mi} = A_n^m$ and $b_n^{me} + b_n^{mi} = B_n^m$, Equation (2) could be written as;

$$V_n^m(\theta,\phi) = R_e\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left[A_n^m\cos(m\phi) + B_n^m\sin(m\phi)\right]P_n^m(\theta) \tag{3}$$

It is observed from Equation (3) that the functions multiplying the Legendre terms appear somewhat like a Fourier series: a harmonic series of cosine and sine terms that, when added, will produce the function they are to represent. There are two computational restrictions; (i) n must be ≥ m, and (ii) the Legendre series must be truncated at a particular value of n.