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Analysis of CHAMP Magnetic Anomalies for Polar Geodynamic Variations

Hyung Rae Kim*, Ralph R. B. von Frese, Chan-Hong Park***, and Jeong Woo Kim******

Goddard Earth Science and Technology, Univ. Maryland, Baltimore County at Geodynamics, Code 921,
GSFC/NASA, Greenbelt, MD 20771, U.S.A*
Department of Geological Sciences, The Ohio State University, Columbus, OH 43210, U.S.A**
Marine Geoenvironment & Resources Division, Korea Ocean Research and Development Inst., Korea***
Dept. of Geoinformation Engineering, Sejong University, Seoul, Korea****

Abstract : On board satellite magnetometer measures all possible magnetic components, such as the core and crustal components from the inner Earth, and magnetospheric, ionospheric and its coupled components from the outer Earth. Due to its dipole and non-dipole features, separation of the respective component from the measurements is most difficult unless the comprehensive knowledge of each field characteristics and the consequent modeling methods are solidly constructed. Especially, regional long wavelength magnetic signals of the crust are strongly masked by the main field and dynamic external field and hence difficult to isolate in the satellite measurements. In particular, the un-modeled effects of the strong auroral external fields and the complicated behavior of the core field near the geomagnetic poles conspire to greatly reduce the crustal magnetic signal-to-noise ratio in the polar region relative to the rest of the Earth. We can, however, use spectral correlation theory to filter the static lithospheric and core field components from the dynamic external field effects that are closely related to the geomagnetic storms affecting ionospheric current disturbances. To help isolate regional lithospheric anomalies from core field components, the correlations between CHAMP magnetic anomalies and the pseudo-magnetic effects inferred from satellite gravity-derived crustal thickness variations can also be exploited. Isolation of long wavelengths resulted from the respective source is the key to understand and improve the models of the external magnetic components as well as of the lower crustal structures. We expect to model the external field variations that might also be affected by a sudden upheaval like tsunami by using our algorithm after isolating any internal field components.

Key Words : CHAMP Magnetic Anomaly, Polar Geodynamics, Magnetic Field Variation.

1. Introduction

The massive earthquake off the west coast of Indonesia on December 26, 2004, registered a magnitude of nine on the modified Richter scale, recorded as the fourth largest earthquake in one hundred years. Chao and Gross (2005) using data from the Indonesian earthquake calculated it affected Earth's

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rotation, decreased the length of day (LOD) by 2.68 microseconds, slightly changed the planet's shape, and shifted the North Pole by 2.5 centimeters in the direction of 145° E. They concluded the earthquake and tsunami caused a LOD change too small to detect, but it can be calculated. It also caused an oblateness change barely detectable, and a pole shift large enough to be possibly identified. They hope to detect the LOD signal and pole shift when Earth rotation data from ground based and space-borne position sensors are reviewed (Chao and Gross, 2005).

In fact, spaceborne magnetometer data have been used to model the long wavelength magnetic fields generated by variations of mantle's electric conductivity (Constable and Constable, 2004). Therefore, it is a relevant conjecture that this devastating surface and subsequent internal geodynamic event may vary the attitude of Earth's magnetic field on a global scale so that this is possibly detected by satellite observations. In particular, if the mantle convection pattern has been affected by the shift of a rotation pole, the magnetic external fields coupled with the electric field generated by the mantle's conductivity may be varied accordingly. This abrupt, short-term variation caused by a sudden geodynamic movement from a global-scale geohazard may enable us to detect in the satellite magnetometer observations.

Recent microsatellites, such as DEMETER (Detection of Electro Magnetic Emissions Transmitted from Earthquake Regions) that already was launched last year, and currently-pending ESPERIA (Earthquake investigations by Satellite and·Physics of the Environment Related to the Ionosphere and Atmosphere), are designed specifically to investigate such variations at the satellite altitudes of about 500 km. The most difficult, however, is to isolate these corresponding signals from the satellite measurements because the spatial wavelengths are apparently coupled with the regional crustal anomaly component. Therefore, separating lithospheric components from satellite-altitude measurement is critical to study the external field features especially in polar regions where the external fields are strongly agitated and unpredicted.

At polar-orbiting sun-synchronized satellite altitude, i.e. 350-700 km, satellite magnetometer measurements include core field (or main field), external field, and crustal (or lithospheric) magnetic field components. Crustal components due to structural and petrological magnetizations are considered to be static. Here in this paper, we implemented state-of-the-art data processing technique to separate these components from CHAMP data in Antarctica. Eliminating these components along with proper core field from the CHAMP observations, we will have new insight on the time-varying external field of the polar region where geodynamic variations in the external field are of great disturbance.

Satellite magnetic data from the POGO, Magsat, Ørsted and CHAMP missions play a critical role in understanding regional or global magnetic anomaly variations due to petrological variations of the crust and upper mantle, and crustal thickness and thermal perturbations (e.g., von Frese *et al.*, 1982; 1990; Mayhew *et al*, 1985, Purucker *et al.*, 1999). Better understanding of crustal magnetic anomaly features also gives more insight to resolve the coupled external magnetic fields that are spatially and temporally varied. Data from satellite observations provide uniform magnetic coverage to within a few degrees of the poles. However, the relatively enhanced density of satellite data at the poles is definitely useful for polar geologic studies that generally lack coverage by conventional near-surface anomaly surveys due to the remoteness and harsh environmental conditions of the polar region.

CHAMP magnetic observations offer significant advantages for Antarctic crustal studies over the data from NASA's Magsat mission. For example, the Magsat data collected only over a 6-month period during austral summer when external field activity is strongest are highly contaminated by non-lithospheric noise in the Antarctic. The CHAMP satellite, by contrast, has been operating since July 2000 and collected with considerably greater accuracy a much larger quantity of relatively low-noise data over several austral winters. The improved CHAMP magnetic data offer significant opportunities for developing new insight on the features and development of the poorly understood south polar crust.

Satellite magnetic crustal sources, in general, reflect both inductive and remanent components of magnetization. As crustal depth increases, remanent and thermal overprints are diminished while viscous magnetization is enhanced as temperature increases to within about 100-150°C of the Curie point of magnetite. The effects of viscous magnetization are in-phase with the induced component and may have a strong effect at satellite altitudes.

Thermoremanently magnetized sources, on the other hand, are located predominantly in the upper crust. These sources produce relatively high frequency signals that are particularly strong at the near-surface, but considerably attenuated at satellite altitudes. Exceptions are the regional signals from extensive areas of oceanic crust that were produced during a long normal polarity interval in the Cretaceous. The effects of the oceanic Cretaceous Quiet Zones are commonly observed at satellite altitudes (e.g., LeBrecque and Raymond, 1982).

2. Antarctic Magnetic Anomalies from Champ Observations

Satellite anomalies from typical global spherical harmonic models, however, can be problematic for polar lithospheric studies because the strong and complex effects from the auroral external fields are only marginally accounted for in the anomaly estimates. Hence, in this study, we use advanced spectral correlation theory to process CHAMP magnetic observations south of 60°S for anomalies with maximum crustal signal-to-noise ratios, where the noise components are composed of external field and other dynamic non-crustal effects.

Our processing of the south polar CHAMP magnetic observations (von Frese and Kim, 2003; Kim *et al.*, 2002) follows the flow chart in Fig. 1. Fig. 2. A shows the crustal thickness model of the Antarctic produced by von Frese *et al.* (1999) using the spectral correlation analysis of free-air and computed terrain gravity effects at satellite altitude. This model has a good agreement with the seismic results available at the Antarctic crust and its surrounding oceans. For further details concerning the use of the model, the reader is referred to von Frese *et al.* (1999). Fig. 2.C gives the related magnetic effects at 400 km that we modeled from crustal thickness variations by Gauss-Legendre quadrature integration, using the core field attributes shown in Fig. 2.B. The chosen susceptibilities for the continental and the oceanic crusts are 0.01 and 0.03 SI, respectively (Kim, 2002). To appreciate more directly

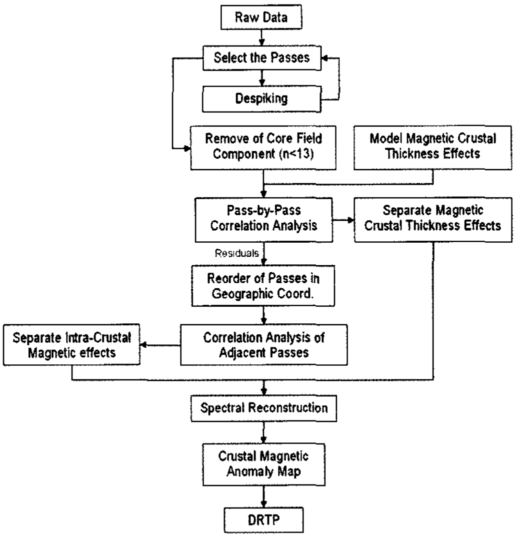

Fig. 1. Flowchart for processing the CHAMP magnetic data for crustal anomalies.

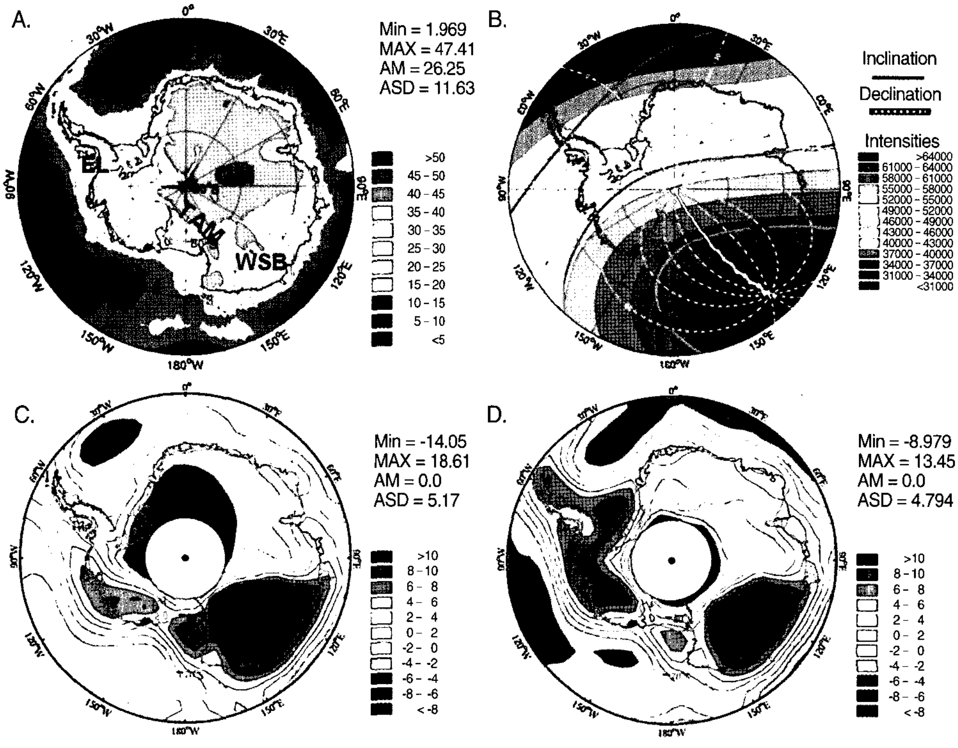

Fig. 2. A) Antarctic crustal thickness variations from gravity and topography data (von Frese *et al.*, 1999). Annotations include the maximum (MAX) and minimum (MIN) amplitude values, the amplitude mean (AM) and amplitude standard deviation (ASD). B) Core field attributes from the CHAMP spherical harmonic model [10]. The magnetic effects (in nT) of the crustal thickness variations are evaluated as total field and differently reduced-to-pole (DRTP) anomalies at 400 km in maps (C) and (D), respectively.

respectively (Kim, 2002). To appreciate more directly the relationships between the crustal thickness variations and the satellite altitude magnetic anomalies reduced the total field anomalies (Fig. 2.C) differentially to the radial pole are shown in Fig. 2.D. The differentially reduced-to-pole (DRTP) anomalies clearly reveal an enhanced image of the continent-ocean edge effects for the Antarctic. Therefore, we note that total intensities of magnetic lithospheric anomalies in the Antarctic where the geomagnetic poles were located nearby Wilkes Subglacial Basin (WSB) were strongly influenced by the core field component. Inaccurate subtraction of the core field component estimates might corrupt to extract the coupled component of the long wavelength magnetic crustal thickness effect signals from the crustal magnetic anomaly estimates.

To facilitate extracting the possible effects due to the thickness variations of the Antarctic crust from the CHAMP data on a track-by-track basis, the magnetic effects in Fig. 2.C were modeled using spherical cap harmonic (SCH) analysis (e.g., Haines, 1985). The maximum spatial index was chosen equal to 30, being the model defined by a total of 250 coefficients on a 30 degrees half angle cap.

As shown in the processing flowchart of Fig. 1, we first removed estimates of the core field from the CHAMP observations using CM model from GSFC/NASA (Sabaka *et al.*, 2002). The residuals were then spectrally correlated with the predictions from SCH model of the crustal thickness effects along each satellite track. Signals in the CHAMP anomaly residuals that were positively correlated with the SCH predictions were extracted and mapped at 450 km altitude, as shown in Fig. 3.A.

The remaining relatively high frequency satellite measurements that were not correlated with the crustal

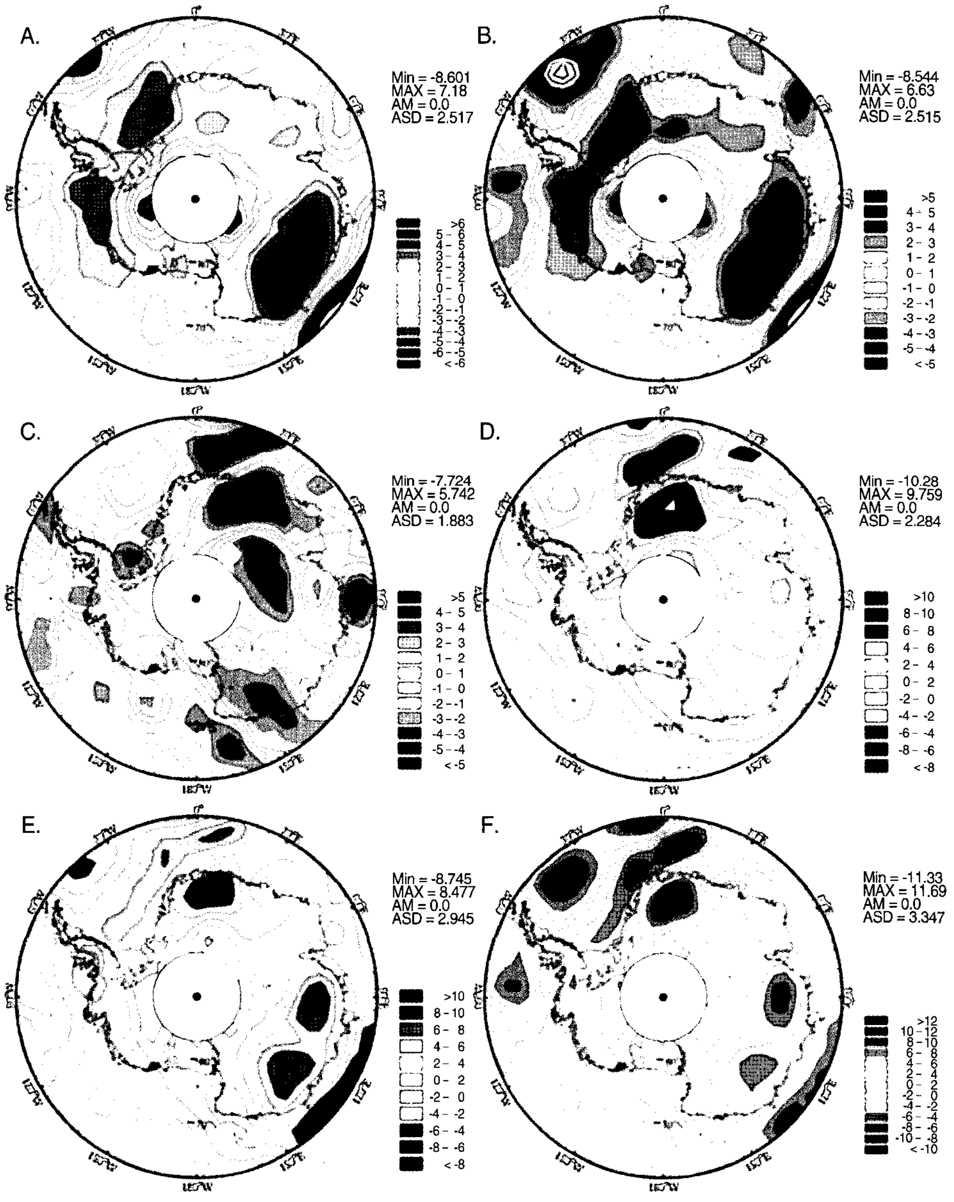

Fig. 3. CHAMP magnetic anomalies at 450 km altitude include A) total field and B) DRTP crustal thickness magnetic effects at contour interval CI = 1 nT; C) total field and D) DRTP magnetic anomalies at CI = 1 nT and 2 nT, respectively; and E) total field and F) DRTP (F) comprehensive crustal magnetic anomalies at CI = 2 nT.

thickness magnetic effects, were next sorted into orbital pairs of nearest-neighbor tracks to extract the static, correlated features that presumably reflect the effects of additional crustal sources (Alsdorf *et al.*, 1994; von Frese *et al.*, 1997). Negative or null correlated signals between tracks separated by distances that are small clearly cannot be related to features of the crust, but rather must be related to the dynamic effects of external fields and other non-crustal noise.

Fig. 3.C gives the estimates resulting from the track-by-track spectral correlation analysis that mostly reflect the intracrustal magnetization variations. The magnetic effects from crustal thickness variations and the intracrustal magnetization variations were then added together and plotted in Fig. 3.E. The DRTP anomalies for the respective maps are also presented in Fig. 3.B, 3.D and 3.F.

3. Conclusions and Discussions

Fig. 3.A and B show the resulting CHAMP magnetic anomaly map that can reflect the Antarctic continent-ocean edge effects. The dominant portion of the large anomalies over Wilkes Subglacial Basin (WSB in Fig. 2.A) appear to indicate the integrated edge effect of the underlying thinned crust (Fig. 2.A) that involves the continent-ocean boundary and thicker crust underlying the Transantarctic Mountains (TAM) on west and the Gamburtsev Mountains (GM) to the east. The intracrustal anomalies over this area are comparatively weakly expressed in Fig. 3.C and D.

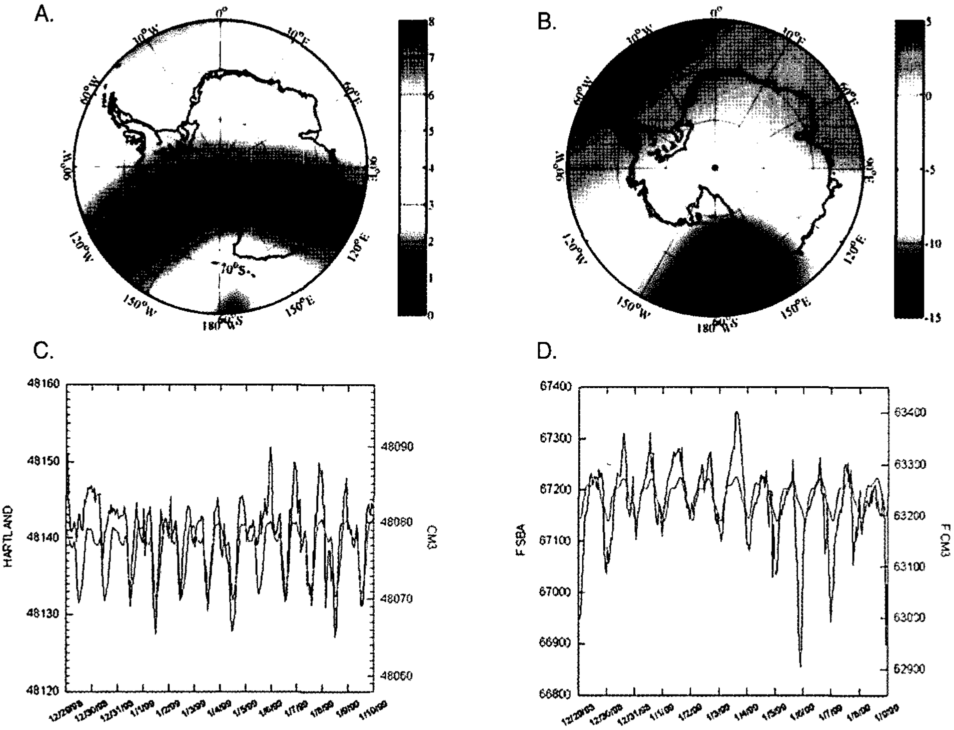

Fig. 4. Induced ionospheric magnetic field at 400 km from the CM4 model (Sabaka *et al.*, 2004). A) for a horizontal component and B) a vertical component. C) is the magnetic diurnal variations (black line) from the Hartland observatory placed in mid latitude (England, 51N, 4.5W), with the predictions from CM (Sabaka et al., 2003) in red line, and D) is from Scott Base Antarctic observatory (78S, 166 E).

A prominent elongated positive intracrustal anomaly overlies Maude Rise (MR) that reflects the remanent magnetization effects of this Cretaceous Quiet Zone (e.g., Kim, 2002; Fullerton *et al.*, 1994). This long linear positive anomaly extends from Maud Rise along the eastern margin of the Weddell Sea Embayment (WSE) to Ellsworth Land (EL) where a series of microplates are assembled (e.g., Dalziel and Elliot, 1982). This linear anomaly is a relatively robust feature because it is also seen in degree 15-90 components of the global spherical harmonic map of the CHAMP magnetic data produced by Maus *et al.* (2005). Further insight on the crustal significance of this feature can result from joint modeling of both satellite and near-surface magnetic observations (e.g., von Frese *et al.*, 1999; Kim, 2002).

We are currently extending this study to include the regional remanent magnetization effects from the Cretaceous Quiet Zones about Antarctica (e.g., Purucker *et al*, 1999). We are also investigating the joint use of satellite and near-surface magnetic anomalies to constrain Curie isotherm estimates and related heat flow variations of the Antarctic crust that may affect the dynamics of the overlying ice sheets.

Once we removed the internal long wavelength crustal components from the satellite measurements, the residuals after removing the main field should be the variations from the external field components. Fig. 4 A and B show the snapshots of the induced ionospheric magnetic fields at 400 km altitude on January 1, 2000 (00:00:00 GMT) over the Antarctica for horizontal and vertical components, respectively. These estimates are derived from the comprehensive model (CM) (Sabaka *et al.*, 2003) that was developed to represent both internal and external magnetic components during the magnetically quiet periods. In particular, the model included the induced magnetic field in the ionosphere caused by electric currents coupled with the mantle conductivity variations. Such long wavelength features with equivalent amplitude ranges of lithospheric field are sporadically screened and intermixed with internal crustal field wavelengths in the measurements and are difficult to isolate. This could be worse especially for the polar regions where the external fields are overwhelmingly agitated. Fig. 4 C) and D) are some examples showing diurnal magnetic variations from two ground magnetic observatories at different locations, comparing with CM predictions. Diurnal variations in (C) are well suited with the model from the Hartland observatory placed in mid latitude (England, 51 N, 4.5W), whereas these variations (D) are not correlated in Antarctic observatory (Scott Base, 78S, 166 E).

Our efforts to resolve the long wavelength magnetic properties and evolution of the lithosphere will significantly accommodate to isolate the external field signals in the satellite measurements that are coupled with regional crustal features in Antarctica. Separating these components along with proper core field from the CHAMP observations will give us new insight on the time-varying external field of the polar region where geodynamic variations in the external field are of great disturbance.

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