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# Regional mapping of the lunar magnetic anomalies at the surface: Method and its application to strong and weak magnetic anomaly regions

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ABSTRACT

We have developed a new method for regional mapping of the lunar magnetic anomalies as the vector field at the surface using the satellite observation, that is the surface vector mapping (SVM). The SVM is based on the inverse boundary value problem with a spherical boundary surface. There are two main procedures for reducing effects of bias and noise on mapping: (1) preprocessing the data to provide first derivatives along the pass, and (2) the Bayesian statistical procedure in the inversion using Akaike's Bayesian Information Criterion. The SVM was applied to two regions: the northwest region of the South Pole-Aitken basin as a strong magnetic anomaly region, and the southeast region of the lunar near side as a weak magnetic anomaly region. Since the results from the different datasets of the Kaguya and Lunar Prospector observations show good consistency, characteristic features of the lunar magnetic anomalies at the surface are considered to be well estimated except for components of wavelength shorter than about 1°. From the results by the SVM, both of the regions show elongation patterns of the lunar magnetic anomalies, suggesting lineated structures of the magnetic anomaly sources.



## 1. Introduction

The origin of the lunar magnetic anomalies is one of the most important issues for the lunar science and has been debated (e.g. Dyal et al., 1974; Fuller, 1974; Lin et al., 1988; Hood and Artemieva, 2008; Garric-Bethell et al., 2009; Gattacceca et al., 2010; Wieczorek et al., 2012; Purucker et al., 2012; Hood et al., 2013). For the global mapping of vector fields, the Lunar Prospector observations at low altitudes were corrected and normalized to 30 km altitude (Richmond and Hood, 2008; Purucker and Nicholas, 2010), while the Kaguya observation during the nominal phase were normalized to 100 km altitude (Tsunakawa et al., 2010). In general, the magnetic fields of short wavelength components are rapidly attenuated at the higher altitude. This attenuation may result in lack of fine and possibly important structures of the lunar magnetic anomalies. Although the near-surface total intensity has been mapped by the electron reflectometry (e.g. Halekas et al., 2001; Mitchell et al., 2008), three components of the magnetic field are more useful for the study of the magnetic anomaly source in comparison with other maps of the topography, geology and so on. Thus the mapping altitude of the vector field is required to be as low as possible.

Distribution of the magnetic field above the surface is attributed to the boundary value distribution if the magnetic field can be expressed in terms of the magnetic potential. One of the boundary values is the radial component of the magnetic field at the surface. The magnetic field of the lunar crust above the surface can be described if the boundary value distribution is given. As an inverse boundary value problem, we can estimate the radial component of the magnetic field at the surface (Tsunakawa et al., 2010).

In the inverse problem, signals of the crustal magnetic field should carefully be separated from noise and bias mainly due to the external field, since the noise and bias are usually amplified via downward continuation. Effects of these amplifications on the surface mapping depends mainly on the strength and wavelength of magnetic anomalies and the three dimensional distribution of observation points. Since these factors vary with respect to the observed region, the regional analysis is suitable for detailed surface mapping of the lunar magnetic anomalies. In the present study, we have developed a statistical method for regional mapping of three components of the crustal magnetic field at the surface from the satellite observation. This method has been applied to two regions: the northwest region of the South Pole-Aitken basin as a strong magnetic anomaly region, and the southeast region of the lunar near side as a weak magnetic anomaly region. We will show the mapping results and discuss characteristic features of the lunar

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magnetic anomalies on the basis of three components of the magnetic field at the lunar surface.

## 2. Datasets

The Kaguya spacecraft, which is a three-axis stabilized spacecraft, observed the magnetic field around the Moon with nearly polar orbit at low altitudes of 6–80 km from December, 2008 to June, 2009, after the high altitude observation. The altitude was gradually lowered with periapsis near the South Pole-Aitken (SPA) basin because strong magnetic anomalies are widely distributed around the SPA basin (e.g. Richmond and Hood, 2008; Mitchell et al., 2008). In particular, the observation was carried out at altitudes lower than 50 km near the SPA basin after March, 2009.

Three components of the magnetic field around the Moon were observed at 32 Hz sampling rate by a triaxial ring-core type magnetometer (Kaguya/MAP/LMAG) with a precision better than 0.05 nT. The detail of the specification and calibration of the Kaguya magnetometer are referred elsewhere (Shimizu et al., 2008; Takahashi et al., 2009; Matsushima et al., 2010; Tsunakawa et al., 2010).

De-trending of the external field was performed for the observations by Lunar Prospector (January–July, 1999; hereafter called LP) and Kaguya (March–June, 2009; hereafter called KG) in the Earth's magnetosphere or on the night side in the solar wind region. We have applied the Bayesian statistical procedure of detrending (Tsunakawa et al., 2010), in which time series of the observed magnetic field for several revolutions are de-trended, while previous methods treat a pass of half orbit (e.g. Richmond and Hood, 2008; Purucker and Nicholas, 2010). The LP data are composed of 5 s averaged data ($\sim$8 km intervals), while the KG data are averaged for 4 s ($\sim$6 km intervals). Since signals of the magnetic anomalies are usually strong for the low altitude datasets, we have used almost all the passes in the analysis.

## 3. Theory

Previous maps of the vector field of the lunar magnetic anomaly have been provided at a certain altitude, for example, 30 km altitude. Those mapping methods are based on the altitude correction applied to the observations at various altitudes. Tsunakawa et al. (2010) point out that the altitude correction of the magnetic anomaly is attributed to the boundary value problem at the surface by the magnetic potential theory. In this section, we briefly review previous mapping methods with respect to the boundary value problem.

### 3.1. Basic theory of the boundary value problem

A magnetic potential $\phi(\boldsymbol{r})$ at a point $\boldsymbol{r}$ outside the magnetic anomaly source is determined from appropriate boundary values, since $\phi(\boldsymbol{r})$ satisfies the Laplace equation, $\nabla^2\phi(\boldsymbol{r}) = 0$.

Assuming a point of $\boldsymbol{r} = \boldsymbol{r}_s$ at the boundary surface $\Omega$, the potential is uniquely determined with a certain Green function, $G(\boldsymbol{r}, \boldsymbol{r}_s)$, where $\nabla^2 G(\boldsymbol{r}, \boldsymbol{r}_s) = -\delta(\boldsymbol{r} - \boldsymbol{r}_s)$,

$$\phi(\boldsymbol{r}) = \iint_\Omega \phi(\boldsymbol{r}_s)\frac{\partial G(\boldsymbol{r}, \boldsymbol{r}_s)}{\partial n}dS \quad : \text{ Dirichlet problem,} \tag{1}$$

$$\phi(\boldsymbol{r}) = \iint_\Omega \frac{\partial \phi(\boldsymbol{r}_s)}{\partial n}G(\boldsymbol{r}, \boldsymbol{r}_s)dS \quad : \text{ Neumann problem,} \tag{2}$$

where $n$ denotes an outward normal direction at the boundary. There is another type of the boundary value problem with a linear combination of $\phi(\boldsymbol{r}_s)$ and $\partial\phi(\boldsymbol{r}_s)/\partial n$,

$$\phi(\boldsymbol{r}) = \iint_\Omega \left\{a\phi(\boldsymbol{r}_s) + b\frac{\partial \phi(\boldsymbol{r}_s)}{\partial n}\right\}G(\boldsymbol{r}, \boldsymbol{r}_s)dS \quad : \text{ Cauchy problem.} \tag{3}$$

In the Cauchy problem, specific values of $a$ and $b(a \neq 0, b \neq 0)$ can give a suitable Green function.

If $\phi(\boldsymbol{r})$ is given, the magnetic field above the surface is calculated from the equation,

$$\boldsymbol{B}(\boldsymbol{r}) = -\mu_0 \nabla\phi(\boldsymbol{r}). \tag{4}$$

Inversely, boundary values are obtained if the distribution of $\boldsymbol{B}(\boldsymbol{r})$ outside the boundary is known. This is called the inverse boundary value problem. Mapping the equivalent source at the surface is regarded as one of inverse boundary value problems as shown in the next subsection.

### 3.2. Previous methods in relation to the boundary value problem

#### 3.2.1. Equivalent source model of vertical magnetizations

It is known that a potential of the magnetic anomaly is expressed with vertical magnetizations at the surface, $\hat{\boldsymbol{m}}(\boldsymbol{r}_s)$,

$$\phi(\boldsymbol{r}) = -\frac{\mu_0}{4\pi}\iint_\Omega \hat{\boldsymbol{m}}(\boldsymbol{r}_s)\cdot\nabla_P\left(\frac{1}{r'}\right)dS, \tag{5}$$

where $\boldsymbol{r}' = \boldsymbol{r} - \boldsymbol{r}_s$ and suffix $P$ denotes the differentiation concerning $\boldsymbol{r}$. The above $\phi(\boldsymbol{r})$ corresponds to magnetic potential in the Dirichlet problem (see Appendix A.1):

$$\phi(\boldsymbol{r}_s) = \mu_0\hat{m}, \quad G(\boldsymbol{r}, \boldsymbol{r}_s) = \frac{1}{4\pi r'}. \tag{6}$$

Therefore magnitude of the vertical magnetization, $\hat{m}$, is equivalent to the potential at the assumed boundary.

#### 3.2.2. Equivalent source model of horizontal magnetizations

Purucker (2008) and Purucker and Nicholas (2010) applied the equivalent source model of horizontal magnetizations at the lunar surface for the altitude correction of the LP observations. Defining the equivalent horizontal magnetization at the boundary as $\tilde{m}(\boldsymbol{r}_s)$, the magnetic potential $\phi(\boldsymbol{r})$ is given from the following equation,

$$\begin{aligned}\phi(\boldsymbol{r}) &= -\frac{\mu_0}{4\pi}\iint_\Omega \tilde{\boldsymbol{m}}(\boldsymbol{r}_s)\cdot\nabla_P\left(\frac{1}{r'}\right)dS \\ &= \frac{\mu_0}{4\pi}\iint_\Omega \tilde{\boldsymbol{m}}(\boldsymbol{r}_s)\cdot\nabla_Q\left(\frac{1}{r'}\right)dS,\end{aligned} \tag{7}$$

where suffix $Q$ denotes the differentiation concerning $\boldsymbol{r}'$.

Using a vector potential $\boldsymbol{A}$, the Neumann type potential of Eq. (2) is written in the following equation (see Appendix A.2),

$$\phi(\boldsymbol{r}) = -\frac{1}{\mu_0}\iint_\Omega \{\boldsymbol{A}(\boldsymbol{r}_s)\times\boldsymbol{n}\}\cdot\nabla_Q G(\boldsymbol{r}, \boldsymbol{r}_s)dS. \tag{8}$$

From the equations of (7) and (8),

$$\tilde{\boldsymbol{m}}(\boldsymbol{r}_s) = -\frac{1}{\mu_0^2}\{\boldsymbol{A}(\boldsymbol{r}_s)\times\boldsymbol{n}\}, \quad G(\boldsymbol{r}, \boldsymbol{r}_s) = \frac{1}{4\pi r'}. \tag{9}$$

Therefore the equivalent source model of horizontal magnetization is regarded as one of the Neumann problems. The horizontal magnetization, $\tilde{\boldsymbol{m}}(\boldsymbol{r}_s)$, corresponds to a horizontal component of the vector potential at the boundary.

#### 3.2.3. Equivalent source model of magnetic charges

Defining surface magnetic charges of a uniformly magnetized body with an arbitrary surface configuration as $\sigma_m(\boldsymbol{r}_s)$, the magnetic potential is expressed in the following equation (see Appendix A.3),