Available online at www.sciencedirect.com

ScienceDirect

Progress in Natural Science 18 (2008) 21–26

Progress in Natural Science

Magnetic rotation imaging method to measure the geomagnetic field

Xiaojun Li *, Jintao Bai, Yongan Li, Xiaoniu Li, Yuanyuan Wang, Xiaoqiang Feng

Institute of Photonics and Photon-Technology, Northwest University, Xi'an 710069, China

Received 31 May 2007; received in revised form 9 July 2007; accepted 9 July 2007

Abstract

A new imaging method for measuring the geomagnetic field based on the magnetic rotation effect is put forward. With the help of polarization property of the sunlight reflected from the ground and the magnetic rotation of the atmosphere, the geomagnetic field can be measured by an optical system installed on a satellite. According to its principle, the three-dimensional image of the geomagnetic field can be obtained. The measuring speed of this method is very high, and there is no blind spot and distortion. In this paper, the principle of this method is presented, and some key problems are discussed.

Keywords: Optical imaging; Magnetic rotation effect; Geomagnetic field; Measurement

1. Introduction

The geomagnetic field is one of the few fundamental physical fields which joins the sun, the earth and the human together. The geomagnetism has many important applications in scientific research, production, human life, aviation, navigation, spaceflight, and military affairs, etc. [1,2]. The result of geomagnetic measurement is widely used in many fields such as earthquake prediction [3], magnetic prospecting [4], magnetic navigation [5], radio communication [6], solar activity prediction [7], and volcano prediction [8], and so on.

Research on the geomagnetic field will be certain to relate to measurement. There are some existing measuring methods of the geomagnetic fields now, which are ground measurement, sea measurement, aeromagnetic measurement, satellite measurement, magnetic observatory, etc. [9,10]. Each of these measuring methods has its own advantages and application areas. As research and application of the geomagnetism go on, demand for good performance of geomagnetic field measurement is becoming greater and greater. The existing measuring methods of geomagnetic field have shown some defects: (1) Measuring speed is low. As two basic existing measuring methods of the geomagnetic field used earlier, the ground measurement and the sea measurement may spend a few years to finish a measurement over a whole national territory or a large sea area, and this may bring a distortion to the measurement results [10]. It will also take a long time for the aeromagnetic measurement and the satellite measurement to finish a measurement task over the whole earth. (2) There are some unreachable regions (the so-called blind spot) in the ground measurement and the sea measurement. Other measuring methods are difficult to reflect the detailed structure of the geomagnetic field and the magnetic local anomaly in some area where the geomagnetic field structure is complex because the measuring point is relatively sparse. (3) Measurement modes of most of the existing methods are limited to zero-dimension (single point measurement) or one-dimension (measurement along orbit of airplane or satellite). It is somewhat difficult

* Corresponding author. Tel.: +86 29 8330 2068; fax: +86 29 8830 3336.
E-mail address: lixiaojun@nwu.edu.cn (X. Li).

1002-0071/$ - see front matter © 2007 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.
doi:10.1016/j.pnsc.2007.07.003

for existing measuring methods to describe the three-dimensional spatial distribution and structure of the geomagnetic field.

The reason for these defects is that the current measuring instruments could only get single-point information at the position of the detector at one moment in the geomagnetic field.

In order to overcome the defects of existing geomagnetism measuring methods, and to get a higher measurement efficiency, we conceived that using an optical imaging method to measure the geomagnetic field.

There are already some researches and applications of optical method of magnetic field measurement. For example, the magneto-optical effect was applied to measure a large current in HV transmission line by measuring the magnetic field around the line [11,12]. By observation and research on the magneto-optic phenomena of celestial bodies, many magnetic stars have been discovered. Magnetic field of white dwarf [13], neutron star [14], galaxy, extragalactic galaxy [15,16], cluster of galaxies [17,18], and even the universe [19] have been measured. But these work all fall into one-point measuring.

There are also many observations and researches on image of magnetic field using optical method. In 1956, Dillon et al. in Bell Laboratory observed the magnetic domain structure in the yttrium iron garnet (YIG) single crystal with a polarizing microscope [20]. The magnetic domain structure in NiO single crystal had also been observed using the magneto-optical effect [21]. And a color imaging technique which can be used to show static and dynamic magnetic domain structure of the material visually was developed with the help of the near-field scanning microscope and the magneto-optical effect [22]. Besides, a rapidly developing magneto-optic eddy current imaging technique has been widely used in nondestructive test to get the image of crackles and defects on basis of the magneto-optical effect and the electromagnetic induction [23].

The present measuring methods of the geomagnetic field still all fall into single-point measurement, and the imaging method has not yet been reported. Only a local observation on the geomagnetic field was attempted. From the satellite, the NASA launched bursting cylinders, which can produce the metal ion cloud suffusing a sphere of thousands of kilometer at high attitude to “color” the invisible geomagnetic field for observing and research.

Based on the previous studies, we put forward a new measuring method of the geomagnetic field. With the help of the polarized property of the sunlight reflected from the ground and the magnetic rotation effect of the atmosphere, the rotation angle of the polarized light can be measured by the optical system on satellite after the light passing through the atmosphere. Then the information of geomagnetic field can be obtained. This new method has a great imaging ability, and structure of the geomagnetic field can be obtained directly.

2. Principle of the magnetic rotation imaging method

2.1. General working principle

The theoretical basis of this measuring method is the Brewster’s law and the Faraday’s magnetic rotation effect. The Brewster’s law tells that light reflected from a medium surface is polarized, and the Faraday’s effect relates the magnetic field to the measurable rotation angle of vibration plane of the polarized light.

Since the sunlight reflected from the ground is polarized (it is usually partial polarized light, and its vibration direction is perpendicular to the incidence plane) [24], we take it as the light source in this measuring method, and take the atmosphere as the medium of magnetic rotation. The rotation angle of vibration direction of the polarized light after it travels through the atmosphere is measured with an optical system on satellite, and then the information of the geomagnetic field can be obtained.

The basic operation principle of this method is shown in Fig. 1, which illustrates that sunlight ray (unpolarized light) is reflected at point A on the ground and becomes a partial polarized light. At this moment, the dominant vibration direction of this partial polarized light is perpendicular to the plane determined by the sun (S), the reflection point A and the detector D. In this case, the initial dominant vibration direction is perpendicular to the plane of the figure. The partial polarized light travels from point A, through the atmosphere, to the detector on the satellite (the orbit plane of the satellite is perpendicular to the plane of the figure). Under the magnetic rotation effect of the atmosphere, and the action of the geomagnetic field, the vibration direction of the partial polarized light turns an angle. The vibration direction of the light at the position of the detector can be determined by polarization analysis and processing. The difference between this vibration direction and the initial vibration direction on the ground is the

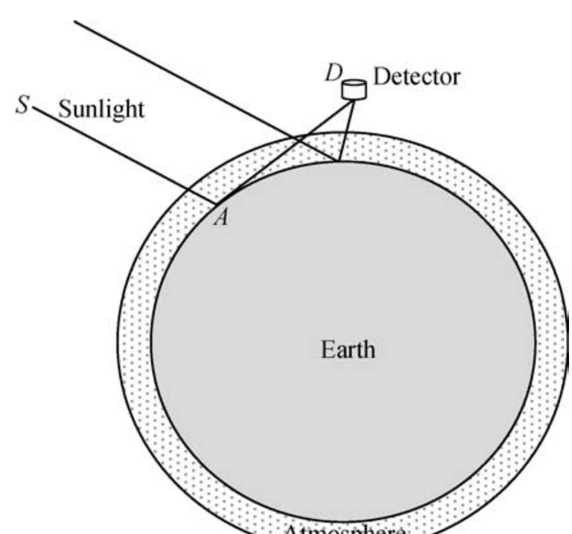

Fig. 1. Basic principle.

rotated angle of the light. This angle contains information of the geomagnetic field.

2.2. Some models

The Faraday's magnetic rotation effect can be illustrated with a formula as below [11]:

$$\theta = \int VH \cdot \mathrm{d}l \qquad (1)$$

where θ is the rotated angle of the vibration plane of the polarized light, V the Verdet constant, H the magnetic intensity, l the distance that the light travels through the medium. We need to measure the rotation angle θ and then calculate the magnetic intensity H. Here the medium is the atmosphere whose Verdet constant changes with temperature, pressure etc.

Then some issues should be considered first: (i) The route and distance that the light travels through the atmosphere during its propagation from the ground reflection point to the detector should be determined, when the satellite is in any position. (ii) The Verdet constant of the atmosphere under different air temperature and pressure should be investigated. (iii) Models of the real atmosphere include distributions of air temperature, pressure and composition should be established.

In order to keep the angle between the incident and reflected sunlight so as to ensure the degree of polarization of the reflected light as high as possible, we install the detector on a sun-synchronous satellite [25]. From the altitude and shape of the satellite orbit, the relative position of the satellite and the Sun, and position of target region on the ground, the route and distance of the light ray that starts from a given ground pixel and travels in the atmosphere could be calculated using geometry method, no matter where the satellite is positioned. The model of the satellite orbit and the model of the route and distance that the light ray travels in the atmosphere are being built now.

The atmospheric models include the distribution model of the air temperature, air pressure and air composition. The primary model is the layered structure. Its notable feature is that temperature, pressure and composition change with altitude [26]. In the dense atmosphere, air temperature has a varying trend as the attitude changes, and the air pressure drops as altitude ascends. In addition, the temperature and pressure also change with alternation of day and night, season, and latitude, while the air composition does not change roughly in the dense atmosphere [25,26].

2.3. Realization of two-dimensional magnetic rotation imaging

The sunlight reflected from the ground target point passes through the atmosphere and arrives at the detector installed on satellite platform. The detector is actually a special aerial camera, and what displays on its imaging plane is only an image of the ground scenery in fact. The vibration direction of the polarized light can be gained only after polarization analysis and processing.

The structure of the detector is shown in Fig. 2. The dotted line frame is inside the detector. The main difference between this detector and a common aerial camera is an added polarization analyzer at the optical path. There is synchronization between the drive device of the polarization analyzer and the data gathering device CCD. When the polarization analyzer is rotating, intensity of the light reaching the CCD will change correspondingly. When intensity of the light received by a given pixel of the CCD reaches its extremum, the rotated angle of the polarization analyzer will indicate the polarization direction of the light reaching this pixel.

The initial polarization direction of the light reflected from every ground target pixel is always perpendicular to its incident plane which determined by the Sun, the ground target pixel and the detector. The difference between the polarization direction of each ray in position of the detector and its initial polarization direction is just the rotation angle of this ray after it travels along the path of light traveling. This rotation angle can reflect information of the geomagnetic field through the atmosphere. After the image information collected by the CCD has been processed, a two-dimensional distribution of the rotated angle of the vibration plane of the light ray within the imaging plane will be formed, and then a two-dimensional image of geomagnetic field can be obtained.

These two-dimensional images will be transmitted to the ground with a radio system for further processing (tomography processing).

The polarization analysis method used here is actually the extinction method. Due to the precision of the extinction method is not high, we attempted to join together the frequency doubling method of polarization analysis and the image processing to improve the precision. Now we have obtained some two-dimensional distribution images of artificial magnetic fields (produced by permanent magnets) in the laboratory [27].

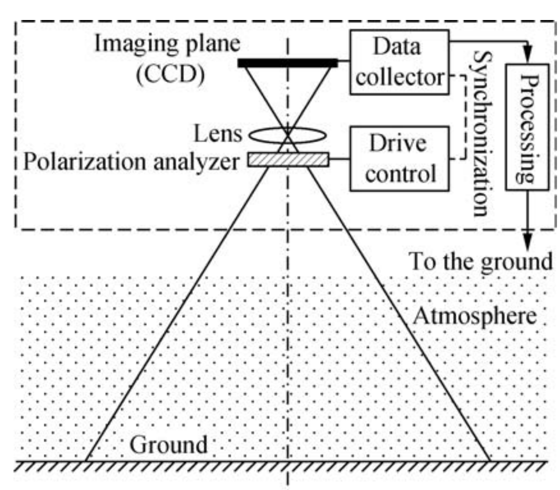

Fig. 2. Structure of detector.

2.4. Restructure of three-dimensional image of the geomagnetic field

It can be noticed from above that: (i) The rotation angle measured by the detector is actually an accumulation of the effect of the geomagnetic field along the route of the reflected light, and the quantity of the geomagnetic field at a given spatial point cannot be determined directly. (ii) What relates directly to the quantity of the rotation is not the geomagnetic field vector itself, but its projection along the direction of light propagation. We used the tomography [28] to solve this problem and to regain the geomagnetic field at every point.

Multiple two-dimensional imaging related to the tomography processing is shown in Fig. 3.

The view direction of Fig. 3 is perpendicular to that of Fig. 1. In Fig. 3, the satellite orbit plane is parallel to the figure's plane. The detector takes a two-dimensional image at point A_1 first, and this image is relative to the geomagnetic field in the area of $a_1b_1c_1d_1$. After the satellite travels a distance and arrives at point A_2, the other two-dimensional image is taken, which is relative to the geomagnetic field in the area of $a_2b_2c_2d_2$. As the satellite travels continually, a series of two-dimensional images will be obtained. The adjacent image areas are intersecting and overlapping. This means a series of two-dimensional measurement of a same area (the overlapping area of the multiple imaging) are taken from different observation directions. Then the geomagnetic field vector (including amplitude and direction) at any spatial point can be gained by the tomography technique.

The tomography method used here is slightly different from the common tomography technique. Firstly, configuration of the light path is different. Secondly, the geomagnetic field is a vector. So the common tomography should be improved before being used here. However, the principle and main idea of the tomography we used is the same as that of the common tomography. The tomography algorithm is being built now. We will introduce it in another paper.

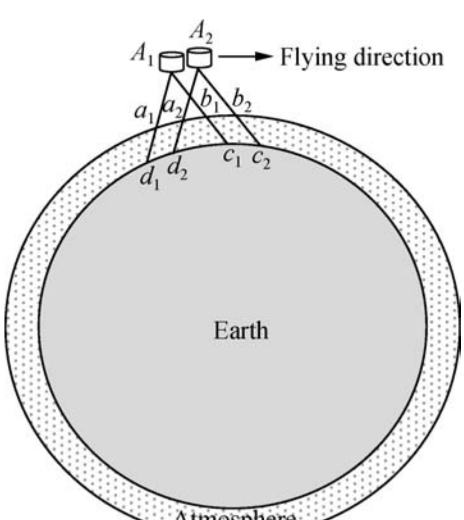

Fig. 3. Multiple imaging while the satellite flying.

After an image processing using the tomography technique is finished, the three-dimensional spatial image of the geomagnetic field is constructed. In fact, the three-dimensional image cannot be displayed directly. The so-called three-dimensional image here is actually an aggregate of the data of the geomagnetic field in a three-dimensional space. To meet a special demand, a two-dimensional image in an arbitrary plane (or curved surface) can be drawn from these data by a computer.

2.5. Some explanations

Because the magneto-optical effect of the atmosphere is utilized, this method is only applicable to measure the geomagnetic field within the atmosphere (strictly within the dense atmosphere), and it is not able to measure the geomagnetic field beyond the atmosphere.

The magnetic rotation effect is dependent of light wavelength. Under the same condition, different wavelength of the light will lead different rotation angle [11,29]. So what should be applied in the measurement is monochromatic light, not polychromatic light. A majority of the earth surface is covered with oceans, and the Earth appears as a blue planet. That is to say, the majority of reflected light from the earth surface is blue. At the mean time, blue light is a short wavelength visible light, and its magnetic rotation is relatively high. Therefore, we selected the blue light in this method. This is easy to be carried out technically. Although the light reflected from the ground is polychromatic, we only need to add a blue light filter of given wavelength (for example 450 nm) into the optical path of the detector to let the light with given wavelength pass through and obstruct the light with other wavelengths.

The magnetic rotation is a property of the polarized light. In general, the reflected light from the Earth surface is partial polarized light instead of linear polarized light. It can be expected that the more this partial polarized light is similar to linear polarized light, the easier its magnetic rotation can be detected. According to some experiments, the Brewster's angle of water is about 55°, and the polarization degree of reflected light from desert, soil, or rock reaches maximum when its incidence angles is 63°, 75°, or 64°, respectively [24]. Since the majority of the Earth surface is covered with water, in order to make polarization degree of the reflected light from the Earth as great as possible, we set the incident angle of light at about 60° mainly according to the Brewster's angle of water and giving some consideration to other representative earth surface such as desert, soil and so on.

Thickness of the dense atmosphere is about 100 km, and the angle between the reflected light ray and normal line of the ground is about 60°, thus the distance that the reflected light travels in the dense atmosphere is about 200 km. In blue light waveband, the Verdet constant of air is around

$10^{-4\prime}$/cm·mT. And average intensity of the main geomagnetic field within the dense atmosphere is approximately 0.05 mT. Intensity of local magnetic anomaly field is about 0.01 mT, and the magnetic storm is about 500 nT [1]. According to Eq. (1), the total rotation angle of the reflected light ray caused by the main magnetic field, the local magnetic anomaly field, or the magnetic storm after the light passing through the atmosphere is about 1.7°, 20′, or 1′, respectively (the magnetic rotation outside the dense atmosphere is negligible). So the main field and the local magnetic anomaly field can surely be measured effectively by this method, and with a sensitive polarization analyzer and a sensitive imaging device, it is also possible that the magnetic storm can be measured effectively.

Due to the lack of the data of variation of the magnetic rotation property of air which changes with temperature and pressure, we cannot effectively estimate how much the irregularity and nonuniformity of the atmosphere influence on the measurement results now. It can be predicted that the irregularity and nonuniformity in the atmosphere will surely impair the measurement performance to some degree. Only after the experiments on magnetic rotation of atmosphere are finished, we can know whether the irregularity and nonuniformity of the atmosphere will cause remarkable impairment.

3. Characteristics of the magnetic rotation imaging method

Based on its working principle, the magnetic rotation imaging method has some advantages: (1) This method is able to obtain the images of the geomagnetic field, giving us a visual impression of the geomagnetic field. (2) Measurement speed of this method is very high. With the well designed orbit of the sun-synchronous satellite and the well designed width of the measurement band on the ground, a measurement over the whole earth is expected to be finished in several days. This also avoids a distortion on the measurement result led by a too long measurement period. (3) As an imaging method, the measuring points (or pixels) are arrayed close to each other. There are no vacancy areas among the pixels on the ground. So there is no blind spot in the measurement by this method. Furthermore, the resolution can be improved with high resolution imaging apparatus. As a means of overall survey, ground resolution of this method can reach the order of magnitude of several hundred meters, which quite outgoes traditional overall survey methods of geomagnetic field. (4) This method has a three-dimension resolution. Therefore a three-dimensional picture of the geomagnetic field can be obtained. Geomagnetic field at different altitude can be measured at same time.

However, it should be noted that, since the measurement result is influenced by atmosphere condition, precision of this method is lower than that of the current methods.

Because of above mentioned characteristics such as visualization, three-dimension ability, high speed, and lower precision, this method is suitable for a overall survey. In practice, it should be used together with the traditional methods. The new method can be applied to an all-weather and near real-time monitoring on the geomagnetic field all over the world, and to find magnetic anomaly at any moment; and the traditional methods can be used for precise and detailed measurement in key regions and magnetic anomaly region. The combination of the new method and the traditional methods will greatly improve the efficiency and accuracy of the geomagnetic field measurement.

4. Summary

The magnetic rotation imaging method is a complicated technical system. We have successfully established its fundamental principle and main structure. The research on this topic is just at the beginning. Now, some experiments on ground reflection have been finished [24]. Magnetic rotation imaging is being simulated in laboratory, and some two-dimensional images of magnetic field around permanent magnet have been obtained [27]. Algorithm of the tomography is being developed. Experiments on magnetic rotation property of air are progressing. Models of atmosphere and orbit of satellite are being built too. At the meantime, it is necessary to study the influence of the irregularity and nonuniformity of the atmosphere on the capability and precision of this method.

References

[1] Xu WY. Geomagnetism (in Chinese). Beijing: Earthquake Press; 2003, p. 1–63.
[2] Li GD. Modern magnetism (in Chinese). Hefei: University of Science and Technology of China Press; 1999, p. 280–6.
[3] Gershenzon NI, Gokhberg MB. Earthquake precursors in geomagnetic field variations of an electrokinetic nature. Izv Acad Sci USSR Phys Solid Earth 1992;28(9):809–13.
[4] Nabighian MN, Grauch VJS, Hansen RO, et al. The historical development of the magnetic method in exploration. Geophysics 2005;70(6):33ND–61ND.
[5] Wiegand M. Autonomous satellite navigation via Kalman filtering of magnetometer data. Acta Astronaut 1996;38(4–8):395–403.
[6] Jacobsen B, Jodalen V, Cannon PS, et al. HF radio propagation at high latitudes under quiet and disturbed geomagnetic conditions. IEE Conf Pub 2000:187–91.
[7] Wilson RM. A prediction for the size of sunspot cycle 22. Geophys Res Lett 1988;15(2):125–8.
[8] Law LK, Auld DR, Booker JR. A geomagnetic variation anomaly coincident with the Cascade volcanic belt. J Geophys Res 1980;85(B10):5297–302.
[9] Яновский БМ (translated by Liu HX, et al.). Geomagnetism (in Chinese). Beijing: Geology Press; 1982. p. 24–31.
[10] Ni YS. Concise tutorial of geomagnetism (in Chinese). Beijing: Earthquake Press; 1990, p. 264–71.
[11] Liu GQ, Le ZQ, Shen DF. Magnetic optics (in Chinese). Shanghai: Shanghai Science and Technology Press; 2001, p. 30–52, 227–31.
[12] Ning YN, Chu BCB, Jackson DA. Miniature Faraday current sensor based on multiple critical angle reflections in a bulk-optic ring. Opt Lett 1991;16(24):1996–8.
[13] Angel JR, Borra EF, Landstreet JD. The magnetic fields of white dwarfs. Astrophys J 1981;45(3):457–74.
[14] Bignami GF, Caraveo PA, Luca AD, et al. The magnetic field of an isolated neutron star from X-ray cyclotron absorption lines. Nature 2003;423(6941):725–7.

[15] Spoelstra TAT. The galactic magnetic field. Sov Phys Usp 1977;20(4):336–42.
[16] Kronberg PP. Galactic and extragalactic magnetic fields in the local universe: An overview. AIP Conf Proc 1998;433(1):196–211.
[17] Kronberg PP. Intergalactic magnetic fields and implications for CR and γ ray astronomy. AIP Conf Proc 2001;558(1):451–62.
[18] Dennison B. On intracluster Faraday rotation. I Observations. Astron J 1979;84(6):725–9.
[19] Bernardis PD, Masi S, Melchiorri F, et al. Extragalactic infrared backgrounds, polarization, and universal magnetic field. Astrophys J Lett 1989;340(2):L45–8.
[20] Dillon JF. Optical properties of several ferrimagnetic garnets. J Appl Phys 1958;29(3):539–41.
[21] Roth WL. Neutron and optical studies of domains in NiO. J Appl Phys 1960;31(11):2000–11.
[22] Hartmann U. High-resolution magnetic imaging based on scanning probe techniques. J Magn Magn Mat 1996;157/158:545–9.
[23] Nath S, Sun B, Chan M, et al. Image processing for enhanced detectability of corrosion in aircraft structures using the Magneto-Optic Imager. Proc SPIE Int Soc Opt Eng 1996;2945:96–103.
[24] Li X, Chen XY, Li XJ. Experimental study on polarization characteristic of the reflected light on representative ground. Acta Photonica Sin (in Chinese) 2005;34(Z2):44–6.
[25] Qian J. Basis of space technology (in Chinese). Beijing: Science Press; 1986, p. 0–27, 57–81.
[26] Xu YM, Liu HN, Xu GY. Conspectus of atmosphere science (in Chinese). Beijing: Science Press; 2000, p. 3–28.
[27] Wang YJ. Studies of photographing for magnetic base of polarized light Faraday magneto-optic effecting (in Chinese). Dissertation of master's degree. Northwest University, Xi'an; 2006. p. 46–61.
[28] Wang ZJ, Wu SD. Imaging optics (in Chinese). Beijing: Science Press; 1991, p. 295–336.
[29] Chen XY, Li X, Li XJ. Experimental study on the magnetic rotation effect of liquid material. Acta Photonica Sin (in Chinese) 2005;34(Z2):17–9.