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# The Borok INTERMAGNET magnetic observatory

A. Chulliat[1] and S. Anisimov[2]

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[1] The Borok Geophysical Observatory (BGO) was established by the Schmidt's Institute of Physics of the Earth of the Russian Academy of Sciences (IPERAS) in 1957 under the International Geophysical Year program, as a central station of a mid latitude region observing the ULF geomagnetic field pulsations. In April 2004, the BGO and the Institute of Physics of the Earth in Paris (IPGP) installed new magnetometers, after which the observatory gained official INTERMAGNET magnetic observatory status. INTERMAGNET is a global network of cooperating digital magnetic observatories, adopting modern standard specifications for measuring and recording equipment and transmitting data in quasi-real time via Geomagnetic Information Nodes to the scientific community. Main results and future developments of the Borok INTERMAGNET observatory are presented. Almost ten years after the launch of the Ørsted magnetic satellite and a few years before that of the ESA Earth Explorer mission *Swarm,* the role of ground magnetic observatories such as Borok as evolved but remains essential. *INDEX TERMS:* 1555 Geomagnetism and Paleomagnetism: Time variations: diurnal to decadal; 1560 Geomagnetism and Paleomagnetism: Time variations: secular and longer; 1594 Geomagnetism and Paleomagnetism: Instruments and techniques; *KEYWORDS:* Borok Geophysical Observatory, INTERMAGNET, magnetic observatories, geomagnetic jerks, geomagnetic data.

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## Introduction

[2] There is a long history of magnetic observations in Borok. Since the establishment of the Borok Geophysical Observatory (BGO) by the Schmidt's Institute of Physics of the Earth of the Russian Academy of Sciences (IPERAS) in 1957, ultra-low-frequency (ULF) geomagnetic pulsations have been recorded in Borok. From 1976 to 2001, a magnetic observatory was in operation on the BGO campus, under the responsibility of the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN). The geomagnetic field was recorded on photographic paper by a three-component Bobrov-type magnetometer. Since 1998, geomagnetic variations have been recorded by a triaxial fluxgate magnetometer belonging to SAMNET, the UK Sub-Auroral Magnetometer Network.

[3] In 2002, IPERAS and BGO started a collaboration with the Institute of Physics of the Earth in Paris (IPGP) to install and operate an INTERMAGNET magnetic observatory in Borok. INTERMAGNET is the global network of digital magnetic observatories adopting modern standard specifications for measuring and recording the Earth's magnetic field variations on long time scales. Data from INTERMAGNET observatories are transmitted in quasi-real time via Geomagnetic Information Nodes to the scientific community and are available at www.intermagnet.org. INTERMAGNET has regularly expanded since its foundation in the late 1980s and now comprises more than hundred observatories throughout the world (107 in 2007). In April 2004, BGO and IPGP installed new magnetometers in Borok, after which the observatory gained official INTERMAGNET magnetic observatory (IMO) status.

[4] One of the main goals of INTERMAGNET is to aid in the establishment of new observatories or the upgrade of existing facilities in areas where the density of IMOs is low, in order to obtain a more homogeneous distribution of IMOs at the Earth's surface. From this point of view, the Borok IMO is a very valuable addition to the global network, since the closest IMO in the West direction is Nurmajarvi (Finland), located 1403 km from Borok, while the closest IMOs in the East direction are Alma Ata (Kazakhstan) and Novosibirsk (Russia), located 3602 km and 4086km from Borok, respec-

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[1] Institut de Physique du Globe de Paris – CNRS, Paris, France
[2] Borok Geophysical Observatory, Institute of Physics of the Earth of the Russian Academy of Sciences, Borok, Yaroslavl' Region, Russia

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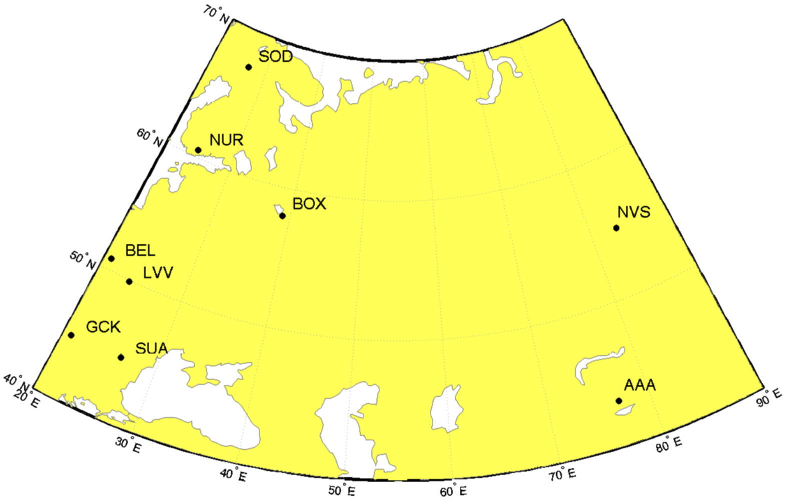

**Figure 1.** Geographical locations of the Borok INTERMAGNET magnetic observatory (of IAGA code BOX) and its nearest neighbors: Novosibirsk (NVS) and Alma Ata (AAA) in the East direction; Sodankyla (SOD), Nurmijarvi (NUR), Belsk (BEL), Lviv (LVV), Grocka (GCK) and Surlari (SUA) in the West direction.

tively (Figure 1). Also, Borok is one of only three magnetic observatories in Russia having the IMO status, and the only one in the European part of Russia.

[5] The present paper describes the layout and instruments of the Borok INTERMAGNET observatory. It presents the data acquired since 2004 and assesses their quality. Finally, the future of ground magnetic observatories such as Borok in the magnetic satellite era is briefly discussed.

## Layout and instrumentation

[6] The magnetic observatory is installed in the premises of BGO's Geoelectromagnetic Monitoring Laboratory, which includes several pavilions dedicated to electric and magnetic measurements (Figure 2). One pavilion is used as the variation room, containing the continuously recording magnetometers mounted on stable pillars in a thermally controlled environment. Another pavilion, at about 100 m distance from the first one, is used as the absolute house, containing the equipment for absolute measurements of the geomagnetic field (Figure 3).

[7] The three components of the Earth's magnetic field are measured by an IPGP VM391 triaxial fluxgate magnetometer (Figure 4). This instrument, developed by IPGP since the mid-1990s, is installed in all IPGP magnetic observatories and in several other magnetic observatories throughout the world [*Courtillot and Chulliat,* 2008]. It satisfies the current INTERMAGNET minimum requirements and is regularly modernized in order to follow the evolution of international standards. One of its main characteristics is that it is homocentric, that is, it measures the three components of the field at the same point. This property is particularly useful in locations where the local gradient is high, such as volcanic islands.

[8] The vector magnetometer samples the magnetic field at 0.2 Hz and one-minute values are produced using the standard INTERMAGNET Gaussian digital filter [*St-Louis,* 2007]. In the same pavilion, the modulus of the magnetic field is measured every minute by a Geomag SM90R Overhauser-type scalar magnetometer. Vector and scalar

**Figure 2.** Pavilions dedicated to electric and magnetic measurements in Borok Geophysical Observatory. The absolute house is the first from the right and the variation room is the first from the left.

**Figure 3.** Interior view of the absolute house.

one-minute data are acquired by an IPGP ENO2 data logger, which is based on a PC system, and transmitted to the INTERMAGNET Geomagnetic Information Node (GIN) in Paris via email within 72 hours.

[9] An important goal of magnetic observatories is to record the geomagnetic secular variation over decades and even centuries. Yet existing vector magnetometers unavoidably drift on such long time scales, due to the aging of the device. The drift of today's good instruments is small (about 5 nT per year or less), but not regular in time and therefore unpredictable. Its magnitude can reach several nT per year, which is larger than the desired accuracy for secular variation measurements. Additional sources of drift include temperature variations (if the temperature control is not perfect) and slow pillar movements, which are often unavoidable. For these reasons it is necessary to make quite frequent absolute measurements, that is, precise determinations of the declination and inclination using a fluxgate theodolite [*Jankowski and Sucksdorff,* 1996]. The vector value is then reconstructed using measurements of the modulus by the scalar magnetometer, which drift is assumed negligible.

[10] From April 2004 to September 2007, the fluxgate theodolite used in Borok was a LEMI 203 fluxgate magnetometer mounted on an MG2KP amagnetic theodolite. This apparatus was changed in September 2007 and the observatory is now equipped with a Bartington Mag01H single-axis fluxgate magnetometer mounted on a Zeiss 010A amagnetic theodolite. The azimuth mark was also changed and slightly displaced; the absolute pillar remained the same. Magnetic field differences between the absolute pillar and the variation pillars are regularly measured by an additional scalar magnetometer, in order to detect changes in the local field gradient. Note that the horizontal gradient within the absolute house is less than 2 nT/m, making it a very good absolute house by international standards [*Jankowski and Sucksdorff,* 1996]. Since the opening of the observatory, absolute measurements have been made twice a week, in agreement with INTERMAGNET recommendations [*St-Louis,* 2007].

## Accuracy and availability of data

[11] The final accuracy of the data depends on many factors. The first of them is the quality of the baselines, that is, the calibration curves that are used to correct the slow drift in time of the vector magnetometer in order to produce definitive data. Baselines for the Borok observatory are obtained for the $H$ (horizontal), $D$ (declination) and $Z$ (downward vertical) components by fitting a spline curve to the correction values deduced from the absolute measurements. Each year, the spline curve is calculated using data from December of the previous year to January of the following year, in order to avoid discontinuities from one year to the other.

[12] As an example, baselines for the year 2006 are represented in Figure 5. More than hundred absolute measurements were made in 2006 by BGO observers (each one represented by a coloured square), making it possible to finely follow the magnetometer drift. For each component, the quality of the absolute measurements may be assessed by calculating the standard deviation of the differences between the measurements and the baseline curve. The obtained standard deviations are 0.44 nT for $H$, 0.39 nT for $Z$ and 11.6 arcsec for $D$, which are well within INTERMAGNET requirements. Calculated baseline curves have an amplitude of about 8 nT for the $X$ and $Z$ components, and about 2 arcmin for the declination. These variations are caused by slow temperature variations in the magnetometer room, which can reach several degrees per month. They are not a problem as long as regular and frequent absolute measurements are made, which has been the case ever since the installation of the observatory.

[13] Another way to assess the quality of the measurements is to look at the scalar residual, that is, the difference between the field modulus directly measured by the scalar magnetometer and the modulus calculated from the vector measurement (after correction of the drift by the baseline curve). As can be seen on Figure 6, the scalar residual of hourly mean values remained less than 2 nT during the year 2006. As a result, the uncertainty on definitive values is estimated at ±3 nT in 2006, based upon the scalar residual and the statistical distribution of absolute measurements. The same uncertainty is found for the 2004, 2005 and 2007 data.

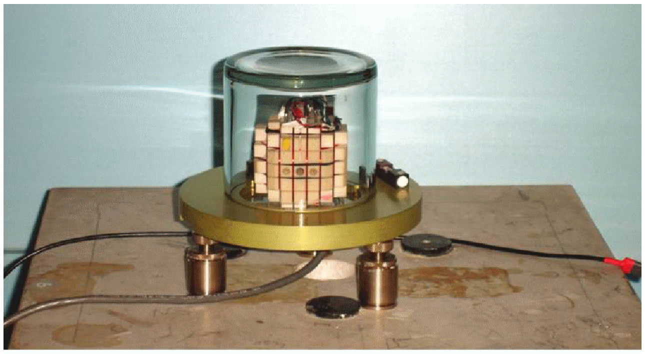

**Figure 4.** The IPGP VM391 fluxgate magnetometer.

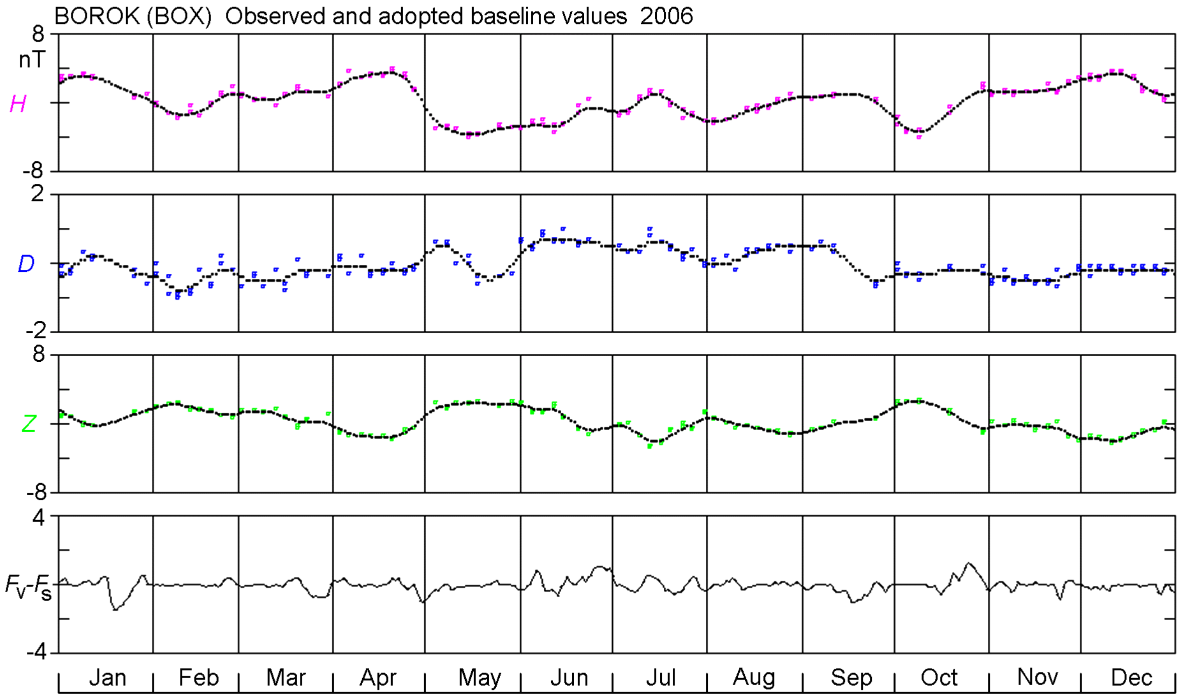

**Figure 5.** Observatory baseline in 2006.

This is well within INTERMAGNET's requirement of 5 nT accuracy on definitive data.

[14] It is also worth noting that there has been very few data gaps since the opening of the observatory: only 0.54 % of the hourly data are missing between April 2004 and December 2007, that is, less than two days per year on average.

[15] Preliminary data are made publicly available within 72 h on INTERMAGNET's website (www.intermagnet.org). Definitive data for each civil year are prepared within a couple of months after the end of the year. They can be retrieved from INTERMAGNET's website or from the website of the Bureau Central de Magnétisme Terrestre (BCMT) in IPGP (www.bcmt.info). After a final cross-check by specialists from other institutions participating in INTERMAGNET, definitive data are published on a DVD (previously a CD-ROM) together with the definitive data from the whole INTERMAGNET network. A report on the data processing and the events happening every year is published in the BCMT yearbook [*Courtillot and Chulliat,* 2008].

## Geomagnetic secular variation in Borok

[16] The geomagnetic secular variation originates in the Earth's outer core, where fluid flows generate the main magnetic field through a dynamo process. A simple (although not perfect) way to average out external field variations in the observatory recordings consists in calculating monthly means and annual means. The resulting series for the Borok observatory are shown in Figure 7, after combining the series from the IZMIRAN observatory (before 2001) and those from the INTERMAGNET one (after 2004). Fortunately the data discontinuity between the two series is not large, thanks to the low magnetic field gradient on the Borok site. It is worth noting that IPGP is currently developing a publicly available database of monthly means from all INTERMAGNET observatories [*Chulliat and Telali,* 2007].

[17] One of the main features of the geomagnetic secular variation is the existence of so-called "geomagnetic jerks", that is, abrupt changes in the secular variation [*Courtillot et al.,* 1978], that occur several times per century [*Mandea et al.,* 2000]. The 1990 geomagnetic jerk is present in the $Y$ component recorded in Borok, as can be seen on Figure 8. The secular variation values in this figure have been computed by taking first differences of monthly means and then applying a one-year sliding average. However, the interruption of the observatory between 2001 and 2004 makes it difficult to properly detect the 1999 jerk [*Mandea et al.,* 2000] and impossible to detect the 2003 one [*Olsen and Mandea,* 2007]. This example shows the importance of having uninterrupted observatory data series to study the geomagnetic secular variation in general, and geomagnetic jerks in particular.

## The future of the Borok IMO

[18] Huge progress has been made in geomagnetism in the recent years thanks to magnetic data provided by the low-Earth orbiting satellites Ørsted and CHAMP, which were

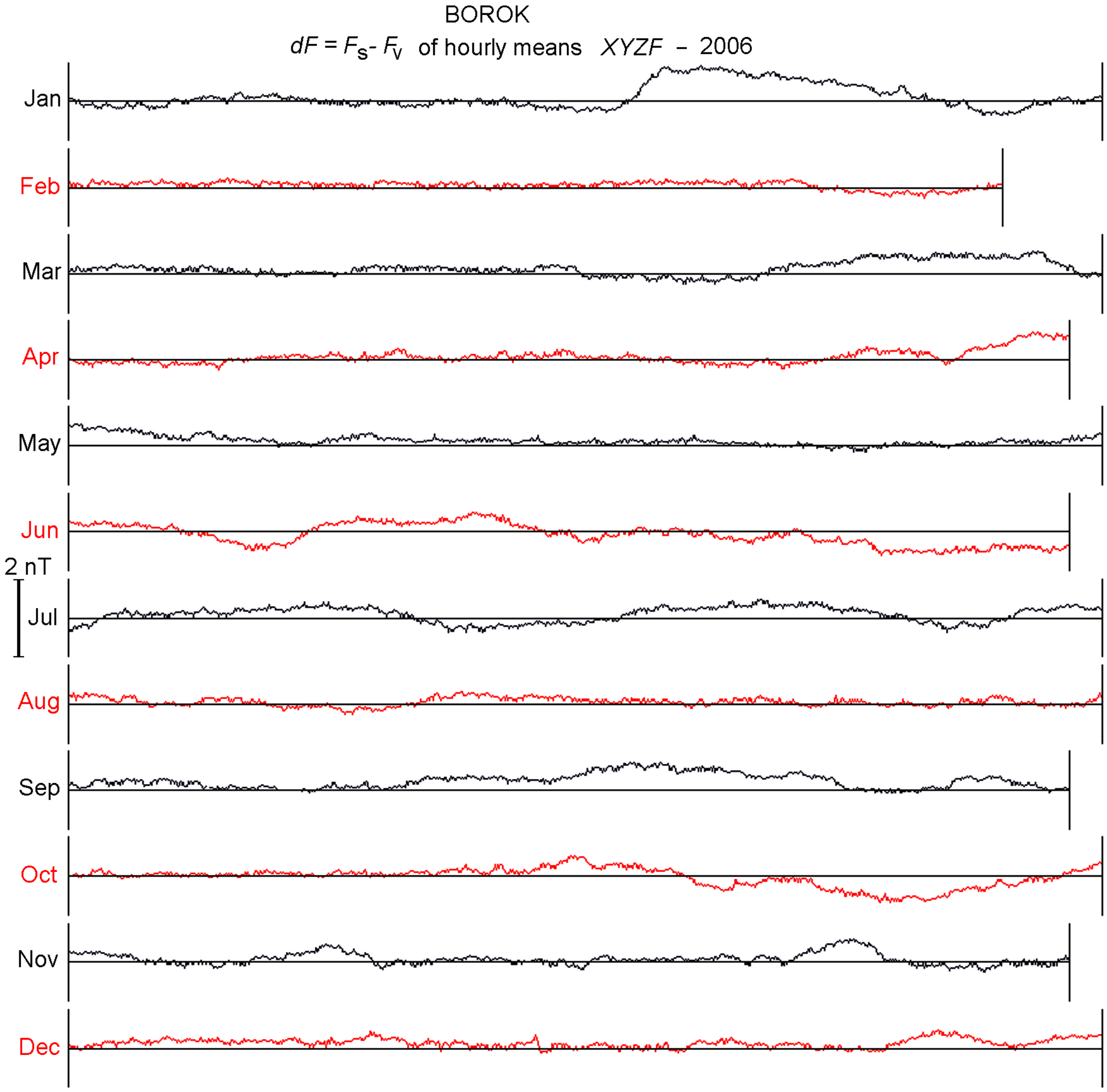

**Figure 6.** Scalar residuals of hourly mean values in 2006.

launched by Denmark and Germany, respectively. These satellites are like flying observatories, equipped with a fluxgate vector magnetometer and a Overhauser-type scalar magnetometer at the end of a boom of several meters length, in order to avoid electromagnetic disturbances from the spacecraft. Unlike ground observatories however, they are moving within the Earth's magnetic field, thus experiencing very different orientations of the field in only a couple of hours. This makes it possible to fully calibrate the vector magnetometer without absolute measurement, simply by minimizing the scalar residual [*Olsen et al.,* 2003].

[19] Magnetic satellites have a quasi-circular, quasi-polar orbit at low altitude (around 700 km for Ørsted, 450 km for CHAMP), so that they provide a global and homogeneous coverage of the Earth's internal magnetic field after orbiting a few days only. Moreover, they slowly drift in local time, which is very useful for studying external field variations. These properties, together with the prospect of the upcoming ESA Earth Explorer Mission *Swarm* [*Friis-Christensen,* 2006] to be launched in 2010, have raised the question of whether magnetic observatories will still be useful and relevant to societal concern in the future [*Kerridge,* 2007]. This may seem a bit odd, at a time when about 100 scientific publications relying directly or indirectly on observatory data are published every year in major geophysics journal [*Newitt,* 2007]. In fact, satellite and observatory data are complementary for many applications, such as separating the various sources in geomagnetic field models, because they have different spatio-temporal properties: observatories are fixed points below the ionosphere, while satel-

lites are moving points above the ionosphere. Observatory data are also used to validate satellite data (and conversely) and they are the only data available for global modeling in years in between satellite missions, such as 2010 for example. Moreover, observatories remain the only source of data for studying the long-term evolution of the ionospheric and magnetospheric magnetic fields [*Chulliat et al.,* 2005], as well as solar activity [*Svalgaard and Cliver,* 2007].

[20] The growing concern for global change and the advent of magnetic satellites bring new challenges and opportunities for magnetic observatories. In order to meet those challenges, INTERMAGNET recommends to increase the sampling frequency of vector data up to 1 Hz, in order to be synchronized with magnetic satellite data, and also to address the growing demand from the space physics community to have one-second magnetic data at the global scale for studying ULF waves in the ionosphere and magnetosphere. This upgrade will be done in the near future at the Borok INTERMAGNET observatory.

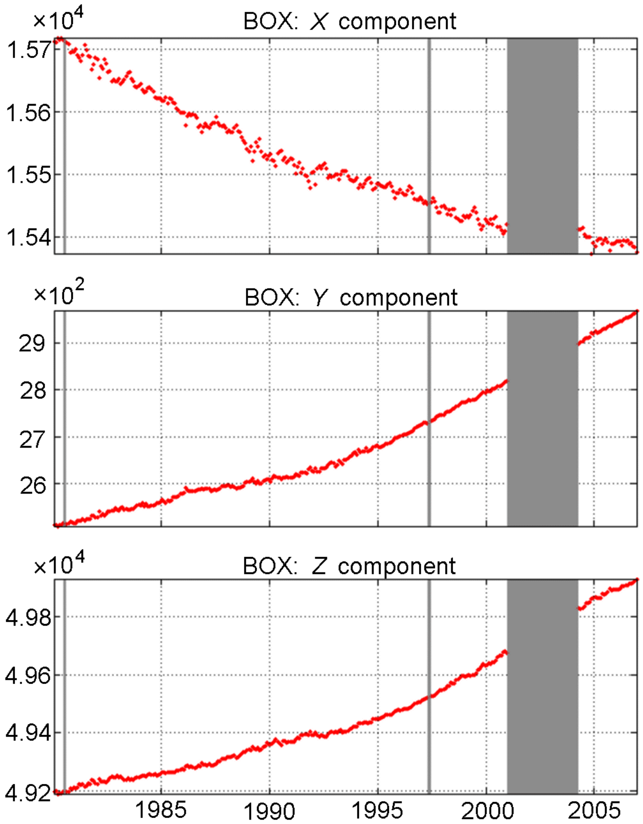

**Figure 7.** Observatory monthly means between 1980 and 2006 for the $X$ (North), $Y$ (East) and $Z$ (downward vertical) magnetic components (expressed in nT). Data gaps are represented by grey rectangles.

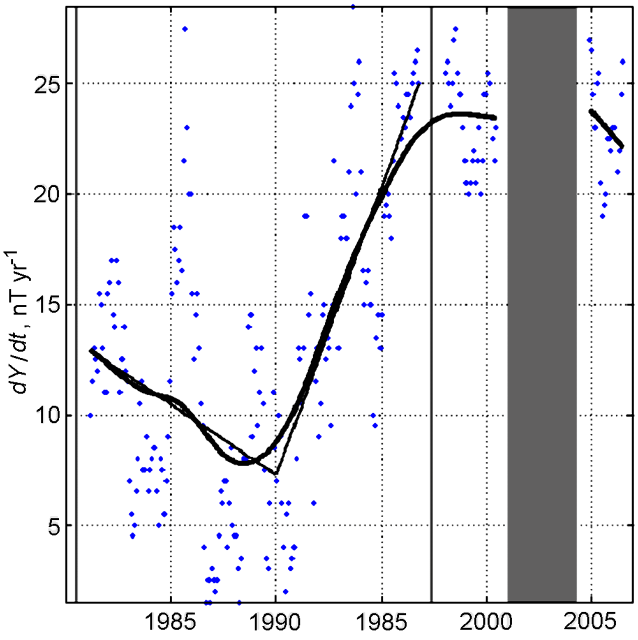

**Figure 8.** Secular variation of the East component ($dY/dt$) from 1980 to 2006 (blue dots), fitted by a smoothed cubic spline (thick black line). It is also fitted by two straight lines, one from 1980 to 1990 and the other one from 1990 to 1999, in order to show the 1990 jerk. Data gaps are represented by grey rectangles.

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A. Chulliat, Institut de Physique du Globe de Paris – CNRS, 4 place Jussieu, 75005 Paris, France (chulliat@ipgp.jussieu.fr)

S. Anisimov, Borok Geophysical Observatory, Institute of Physics of the Earth of the Russian Academy of Sciences, Borok 152742, Yaroslavl' Region, Russia