Intersatellite Comparisons of GOES Magnetic Field Measurements

Frederick Rich[1], Samuel T Califf[2], Paul T.M. Loto'aniu[3], Monica Coakley[1], Alexander Krimchansky[4], and Howard J. Singer[3]

[1]MIT Lincoln Laboratory
[2]Cooperative Institute for Research in Environmental Sciences
[3]National Oceanic and Atmospheric Administration (NOAA)
[4]NASA Space Flight Center

September 29, 2023

Abstract

GOES-16 and GOES-17 are the first of NOAA's Geostationary Operational Environmental Satellite (GOES)-R series of satellites. Each GOES-R satellite has a magnetometer mounted on the end (outboard) and one part-way down a long boom (inboard). This paper demonstrates the relative accuracy and stability of the measurements on a daily and long-term basis. The GOES-16 and GOES-17 magnetic field observations from 2017 to 2020 have been compared to simultaneous magnetic field observations from each other and from the previous GOES-NOP series satellites (GOES-13, GOES-14 and GOES-15). These comparisons provide assessments of relative accuracy and stability. We use a field model to facilitate the inter-satellite comparisons at different longitudes. GOES-16 inboard and outboard magnetometers data suffer daily variations which cannot be explained by natural phenomena. Long-term averaged GOES-16 outboard (OB) data has daily variations of ± 3 nT which are stable within ± 1.5 nT. Long-term averaged GOES-17OB magnetometer data have minimal daily variations (less than ± 1 nT). Daily average of the difference between the GOES-16 outboard or GOES-17 outboard measurements and the measurements made by another GOES satellite are computed. The long-term averaged results show the GOES-16OB and GOES-17OB measurements have long-term stability (± 2 nT or less) and match measurements from magnetometers on other GOES within limits stated herein. The GOES-17OB operational offset (zero field value) was refined using the GOES-17 satellite rotated 180° about the Earth pointing axis (known as a yaw flip).

Hosted file

974988_0_art_file_11422714_s1k0d0.docx available at https://authorea.com/users/668951/articles/669646-intersatellite-comparisons-of-goes-magnetic-field-measurements

Intersatellite Comparisons of GOES Magnetic Field Measurements

Frederick J. Rich[1], Samuel Califf[2], Paul T. M. Loto'aniu[2], Monica Coakley[1], Alexander Krimchansky[3], Howard J. Singer[4]

[1]Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA, USA.

[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA, and National Centers for Environmental Information, National Oceanic and Atmospheric Administration, Boulder, CO, USA.

[3]NASA Goddard Space Flight Center, Greenbelt, MD, USA.

[4]Space Weather Prediction Center, NOAA, Boulder, CO, USA

Corresponding author: Frederick Rich (frederick.rich@ll.mit.edu)

This material is based upon work supported by the Dept of Commerce under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Dept of Commerce.

Key Points:

- GOES-16 magnetic field data have artificial diurnal variations which changes with season. GOES-17 and GOES-18 have minimal variations.
- Daily averages of interference-removed GOES-16 and -17 magnetic field data match simultaneous data from GOES-13, -14 and -15 +/- a few nT.
- When GOES-17 and GOES-18 are separated by 0.2°of longitude, the GOES-17 data match the GOES-18 data within ±1 nT.

Abstract

GOES-16 and GOES-17 are the first of NOAA's Geostationary Operational Environmental Satellite (GOES)-R series of satellites. Each GOES-R satellite has a magnetometer mounted on the end (outboard) and one part-way down a long boom (inboard). This paper demonstrates the relative accuracy and stability of the measurements on a daily and long-term basis. The GOES-16 and GOES-17 magnetic field observations from 2017 to 2020 have been compared to simultaneous magnetic field observations from each other and from the previous GOES-NOP series satellites (GOES-13, GOES-14 and GOES-15). These comparisons provide assessments of relative accuracy and stability. We use a field model to facilitate the inter-satellite comparisons at different longitudes. GOES-16 inboard and outboard magnetometers data suffer daily variations which cannot be explained by natural phenomena. Long-term averaged GOES-16 outboard (OB) data has daily variations of ± 3 nT which are stable within ± 1.5 nT. Long-term averaged GOES-17OB magnetometer data have minimal daily variations (less than ± 1 nT). Daily average of the difference between the GOES-16 outboard or GOES-17 outboard measurements and the measurements made by another GOES satellite are computed. The long-term averaged results show the GOES-16OB and GOES-17OB measurements have long-term stability (± 2 nT or less) and match measurements from magnetometers on other GOES within limits stated herein. The GOES-17OB operational offset (zero field value) was refined using the GOES-17 satellite rotated 180° about the Earth pointing axis (known as a yaw flip).

Plain Language Summary

GOES-16 and GOES-17 are the first two of the R-series of the NOAA's Geostationary Operational Environmental Satellite (GOES). Like previous GOES satellites, they carry two magnetometers (inboard and outboard on a long boom) to measure the magnetic field at geosynchronous orbit (an altitude of approximately 35,786 km above mean sea level). Because these data are used to provide users of spaced-based assets with the knowledge of the space environment and to provide input for research, the accuracy and stability of the new data sets relative to previous data sets are important. There are known variations in the data from the station-keeping thrusters which are removed from the data studied. Previous studies showed that the GOES-16 measurements contain artificial diurnal variations. This study shows that the diurnal variations of the outboard magnetometer data are useful and within specified limits. The GOES-17 measurements do not have significant daily variations. Based on simultaneous measurements from the other GOES satellites, GOES-16 and GOES-17 outboard data are stable over a period of years.

1 Introduction

NOAA Geostationary Operational Environmental Satellites (GOES) have been in operation since 1975. The GOES-R series of satellites (known as GOES-R, S, T and U before launch and GOES-16, 17, 18 and 19 after successful launches) are the latest satellites. GOES-16 was launched November 19, 2016, GOES-17 was launched March 1, 2018 and GOES-18 was launched March 1, 2022. Each satellite carries a magnetometer system to monitor space weather (Singer et al., 1996) for commercial and government users of space. The magnetic field measurements from magnetometers on GOES satellites have contributed significantly to space weather operation, to magnetospheric investigations and to the development of statistical and physics-based models of the magnetosphere. (e.g., Andreeva and Tsyganenko, 2018; Korotova et al., 2018; Tsyganenko and Sitnov, 2005; Korotova et al., 2018). The purpose of this paper is to assess the accuracy and stability of the GOES-16 and GOES-17 magnetic field data relative to the magnetic field data from the previous series (GOES-13, GOES-14 and GOES-15) and from GOES-18. The relative accuracy is most affected by errors in the measurements relative to zero magnetic field in each axis (zero offset) and by stray magnetic fields related to the satellite. Zero offsets can change as the temperature of each element of the sensor unit changes and as the electronic components of the magnetometer age. Temperature changes occur on daily (diurnal) and seasonal cycles. Aging changes may occur over a period of years. Stray magnetic fields can be suppressed by proper design and implementation of the spacecraft and its components. Stray magnetic fields can vary over periods of seconds to years and can contribute to the measured magnetic field.

Herein the GOES-16 and GOES-17 magnetometer data were compared to each other and to magnetic field data from older GOES-NOP satellites. Each comparison is made by differencing simultaneous, one-minute measurements from each of two satellites with a model field used to remove the difference in magnetic field between the satellites due to longitude. By compiling a large set of such comparisons, the accuracy of the measurements by the GOES-R series magnetometers relative to the measurements from the GOES-NOP magnetometers can be assessed. The magnetic field data from the older satellites are also cross-compared in a similar manner to verify that shifts in their zero offsets during time on-orbit are minimal.

The accuracy of the GOES magnetometers are first determined by ground tests and then validated and adjusted as needed during post-launch testing using results from satellite maneuvers, comparisons to nearby satellites, and comparisons to models. After launch, the measurements may be found to be affected by extraneous magnetic fields and possible changes in the calibration. Residual effects have been observed on-orbit in previous instruments. For example, Singer et al. (1996) found that torquer coils created a magnetic signature in the GOES-8 and GOES-9 data. Tsyganenko et al. (2003) found offsets for GOES-8 and GOES-10 of 7.22 nanotesla (nT) and 1.04 nT, respectively, when compared to magnetic field data from the NASA Polar satellite. The measurements of the inboard magnetometer on GOES-13 were degraded by a magnetic field created by thermoelectric current in the material close to the magnetometer (Miller, 2008). Ground and post-launch tests for GOES-16 are detailed in Loto'aniu et al. (2019). Post-launch testing revealed that the GOES-16 inboard (IB) data included significant artificial magnetic fields. Due to the artificial magnetic fields, the GOES-16IB data have not been studied. Loto'aniu et al. (2019) provided initial estimates of the GOES-16 outboard (OB) accuracy post-launch. For this study, we use a more comprehensive GOES-16OB data set than was used in Loto'aniu et al. (2019). The GOES-17 results presented here are the first published study of the GOES-17 magnetometer’s accuracy. The early GOES-18 data are used here to further interpret the GOES-17 data, with other examination of the GOES-18 data in work.

Section 2 discusses the GOES-16, -17 and -18 locations along with a brief description of the magnetometer instrument and coordinate systems. Section 3 details the datasets used and the analysis methods in the inter-satellite comparisons. Section 4 describes the daily variations of the comparisons. Section 5 presents the long-term variations of the inter-satellite comparisons for GOES-16 and GOES-17. Section 6 present the inter-satellite comparisons of GOES-17 and GOES-18 when the two satellite were within 0.2° of longitude to each other. Section 7 describes an inter-comparison of GOES-13 and GOES-15 data to give a perspective of the quality of the GOES-NOP data used in this study. Section 8 states conclusions.

2 GOES Satellites and Magnetometer Instruments

The GOES satellites are in geosynchronous orbit (a circular orbit at an altitude of approximately 35,786 km above mean sea level) with an inclination near 0°. The GOES-R satellites, used for active monitoring of weather systems, are located at 75.2° West geographic longitude (GOES-East) and 137.2° West geographic longitude (GOES-West). The local time at these locations is the Coordinated Universal Time (UTC) minus 5.0 hours and 9.1 hours respectively. When a new GOES satellite is launched, it is located at 89.5° West geographic longitude for a period of a few months for post-launch testing. GOES-NOP satellites have been placed at 75° West and 135° West. During the post-launch test period, a multi-axis maneuver of the satellite is executed to calibrate the magnetometers. After the post-launch test period is completed, the satellite is moved to either the GOES-East or GOES-West position or to a storage location at 105° West geographic longitude until needed to replace a GOES-East or GOES-West satellite.

The GOES-16 satellite was launched November 19, 2016 and subsequently positioned into the post-launch test location. At that time GOES-13 was in the GOES-East location, GOES-14 was in the storage location and GOES-15 was in the GOES-West location. In early 2017, GOES-14 magnetic field data collection began to support the GOES-R mission. Between November 29, 2017 and December 11, 2017 GOES-16 moved to the GOES-East location and was within 0.6° of geographic longitude of GOES-13 location. From December 12, 2017 to December 30, 2017, the two satellites provided data simultaneously for NOAA. After this period, GOES-13 ceased NOAA operations and the satellite was transferred to the U.S. Air Force and re-named the Electro-optical Infrared Weather System Geostationary Satellite 1 (EWS-G1). Since January 2018, GOES-16 has operated as GOES-East.

The GOES-17 satellite was launched March 1, 2018 and subsequently positioned into the check-out location. Between October 15, 2018 and November 13, 2018, GOES-17 moved to the GOES-West position. At that time, GOES-15 moved to an alternate GOES-West position of 128° W (local time of UTC plus 8.5 hours). GOES-14, in the storage location, continued to provide magnetometer data until March 3, 2020 when both GOES-14 and GOES-15 ceased providing data. As of this writing, GOES-17 is no longer operating as GOES-West, but was replaced by GOES-18 in January 4, 2023.

The principal axis (X-axis) of a GOES satellite is radially downward (Earthward). When GOES-R satellites are in the normal "upright" position, the solar panel extends southward from the satellite. For thermal control reasons, the GOES-15 and GOES-17 satellites are put into the inverted orientation, a rotation of 180° about the nadir vector, nominally between the Northern Hemisphere autumnal and spring equinoxes. This rotation is called a "yaw flip".

The magnetic field measuring systems on the GOES-R satellites has been described by Loto'aniu et al. (2019). The system on each satellite consists of two magnetometer sensor units on an 8.55-meter boom. The boom projects from the satellite's principal axis at an angle of 35.5° in the anti-Earthward direction and to the northeast when the satellite is in the upright orientation. The outboard (OB) magnetometer is on the end of the boom and the inboard (IB) magnetometer is attached to the boom 6.35 meter from the satellite (https://www.goes-r.gov/spacesegment/mag.html). The two magnetometers are provided for determining the satellite's magnetic field and providing redundancy. The goal of using the dual measurements to determine and remove the satellite field has not currently been implemented.

As described by Loto'aniu et al. (2019), the magnetometers are identical except for their locations and orientations on the boom. The GOES-16 and GOES-17 magnetometers report each component of the magnetic field vector with a 10 Hz cadence and a one-bit resolution of 0.016 nT in the instrument coordinate system. The design requirements for GOES-R magnetometers included an accuracy of 1.0 nT per axis. After consideration of system errors external to the magnetometer instruments, the magnetic field measurement accuracy requirement became 2.3 nT per axis for a 250 nT magnetic field. Meeting accuracy requirement is challenging and necessitates minimizing magnetic fields from spacecraft systems and other instruments which can contaminate the magnetometer data.

3 Input Data and Analysis Method

Table 1 indicates the data periods used in this study, along with the satellite status. The non-operational periods for GOES-16 and GOES-17 were examined, but data from these periods are not used here. As noted in Table 1, there was a change in the GOES-17 magnetometer temperature setting on February 14, 2019 that affected the data.

Table 1 The span of data used in this study. The asterisk (*) indicates that the GOES-16 and GOES-17 data continued past the study period.

Satellite	Dates for Data Used	Status during Dates Used
GOES-13	01 Jan 2011 – 02 Jan 2018	Operational
GOES-14	01 Jan 2017 – 03 Mar 2020	Standby
GOES-15	01 Jan 2011 – 03 Mar 2020	Operational
GOES-16	12 Dec 2017 – 20 Nov 2022 *	Operational
GOES-17	14 Nov 2018 – 14 Feb 2019	Operation with incorrect magnetometer temperature
GOES-17	14 Feb 2019 - 20 Nov 2022 *	Operational
GOES-18	03 Jul 2022 – 20 Nov 2022 *	Post-Launch Testing

* = continued to operate past this date

The raw data are transmitted from the satellite in packets. Each packet contains one second of data from both instruments. These data packets are processed within the GOES-R Ground System (GS) into Level 0 (L0) data, converted into physical units in several coordinate systems, and stored in Level 1b (L1b) data files. L1b files are promptly made available to users. The L0 data are also received by NOAA's National Weather Service (NSW) Space Weather Prediction Center (SWPC). Using algorithms from the National Environmental Satellite Data and Information prepared by NOAA's Service (NESDIS) National Center for Environmental Information (NCEI), these real-time data are in space weather operations and made available to customers and the public. The L0 and L1b files are also archived in NOAA's Comprehensive Large Array-data Stewardship System (CLASS) and at the National Centers for Environmental

Information, Boulder, CO, USA (NCEI). The various coordinate systems and data levels are described by *Loto'aniu et al.* (2019, 2020). All the data used in this report are in the Earth-Polar-Normal coordinate system (E is radially Earthward and parallel to the spacecraft's X-axis; P is Poleward and parallel to the Earth's spin axis and N is Eastward and perpendicular to the E and P axes).

Calibration values are applied to real-time data from the date of calibration update in the GS. The GOES-R GS does not re-process the archived L0 data into L1b data when new calibration values become available. Hence, MIT LL developed an off-line / local version of the L0 to L1b process to allow the L0 data to be re-processed into L1b-like, full-resolution data files using both the calibration values used by the GOES-R GS and alternate values to test alternate processing methods. In this study, the full-resolution magnetic field data are converted into one-minute averages to remove high frequency variations in the data.

The geomagnetic field varies by longitude along the geographic equator because the axis of the geomagnetic field is tilted from and not co-located with the geographic axis. . We have compensated for satellite location by subtracting a model magnetic field from the one-minute averaged data. Inputs to the model include geomagnetic indices and measurements of the interplanetary environment acquired from the NASA Space Physics Data Facility OMNIWEB (https://omniweb.gsfc.nasa.gov/). We started the study using the models described by Tsyganenko (1989) (hereafter referred to as TS89) and Tsyganenko and Sitnov (2005) (hereafter referred to as TS05). We found that the TS05 model gave more consistent results when compared to measured data than the TS89 model. Therefore, all analysis shown in this paper used the TS05 model for inter-satellite comparisons. The differences between the one-minute magnetic field data and the model field were computed for each satellite. These one-minute, measured-minus-model differences were subtracted from the one-minute, measured-minus-model differences of another satellite for comparisons. For most of this study, the comparisons of two satellites were further compiled into hourly averages to examine the data for artificial diurnal variations. For long-term variations, these hourly averages were compiled into daily averages.

GOES-R satellites have arcjet thrusters which use partially ionized hydrazine gas to maintain the satellite longitude and keep the inclination close to 0°. The thrusters are active for a period ranging from twenty minutes to two hours at intervals of several days. The ionized portion of the exhausted gas contaminates the ambient magnetic field observations *(*Califf et al., 2019, 2020*)*. For this study, all of these periods were excluded from the data set before computing hourly, daily or monthly averages.

The GOES-13, GOES-14 and GOES-15 magnetometer data with 0.512 second resolution were obtained from the National Center for Environmental Information (NCEI) archive. Invalid data were manually removed. The data were compiled into one-minute averages. The one-minute model field data were subtracted from these data before use to compare with magnetic field data from other satellites.

As with any model, the magnetic field model used in this study is an imperfect representation of the geomagnetic field. Because there are disturbances in the environment near the geosynchronous altitude that are limited in longitude, we expect standard deviations of the comparisons to increase with increasing longitudinal separation between satellites even if a perfect model of the average field were available. The closer the geostationary satellites are to each other, the more correlated the model magnetic field measurements tend to be. By combining all comparisons, an upper bound on the relative accuracy and stability of GOES-16OB and GOES-17OB have been determined.

4 Diurnal Variations of GOES-16 and GOES-17 Magnetometer Data

4.1 Diurnal Variations of GOES-16 Magnetometer Data

Figure 1 shows the difference in the measurements between the GOES-13 outboard (OB) magnetometer and the GOES-16 outboard (OB) magnetometer on a day when the two satellites were 0.6° of geographic longitude apart and the Kp index indicated that the geospace environment was quiet. Use of quiet-period ($Kp \leq 1+$) measurements reduces the statistical error of the comparisons. Because of the closeness of the two satellites, a model field was not needed to make the comparison. It is obvious that there is a significant variation in each of the E, P, and N components of the difference. The largest variation is in the P-component which changes by ~10.4 nT during the day. There is geophysical wave activity between approximately 16 and 19 hours UT which is not considered here. What is considered is the trending during the day which indicates a magnetometer-related variation and not a geophysical variation. The few other days when these two satellites were close show similar diurnal variations. This day shows the clearest example. From this example alone, it cannot be determined whether the variations are due to the GOES-13OB or GOES-16OB data.

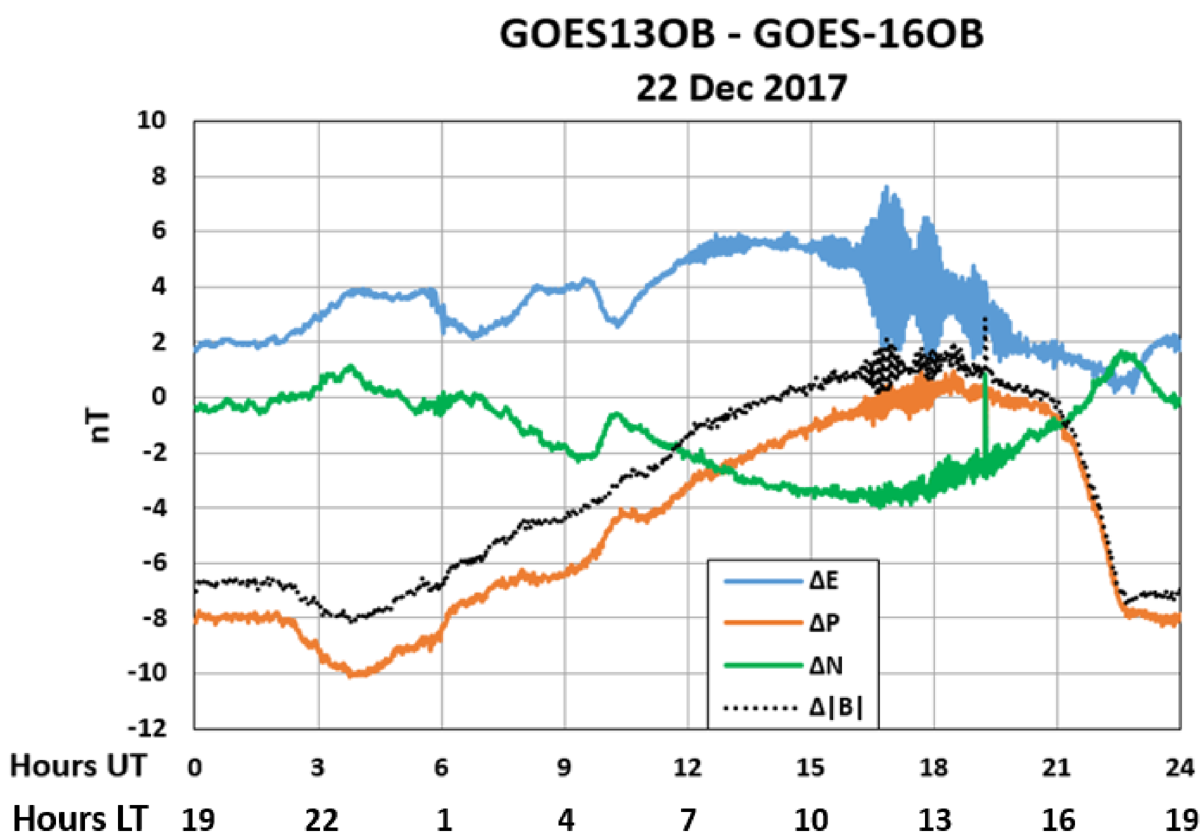


Figure 1 Difference between the magnetic field measured by the GOES-16 outboard magnetometer and the GOES-13 outboard magnetometer on 22 Dec 2017 in E-P-N coordinates

when the two satellites are almost co-located. The magnetospheric environment on this day was very quiet.

By comparing the GOES-13OB data with model subtracted to the GOES-16OB data with model subtracted, shown in Figure 2a and 2b, we find that most of the variation during the day seen in Figure 1 is due to the GOES-16OB data. For example, near 03:00 UT, the difference between the P component and the model is 6.9 nT greater in Figure 2b for GOES-16 than for GOES-13 in Figure 2a.

(a) (b)

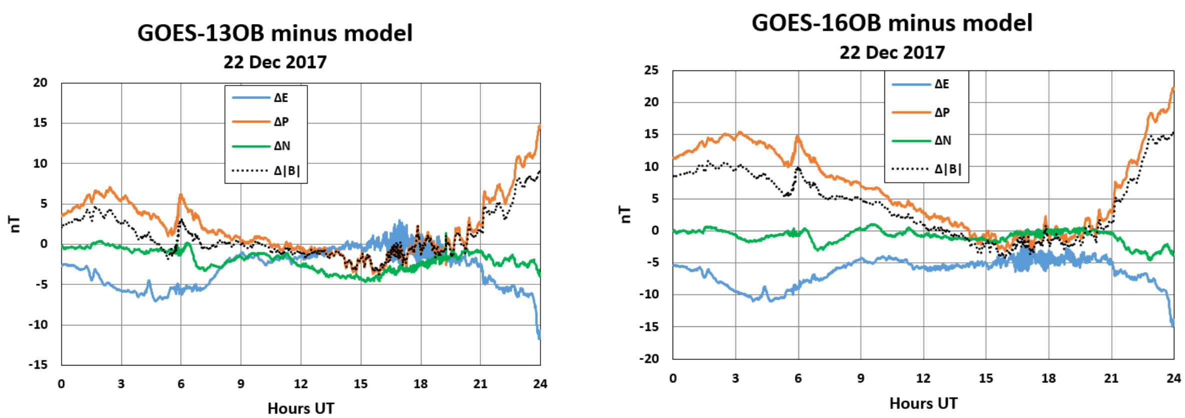


Figure 2 (a) GOES-13 magnetic field measurements minus the model field for 22 Dec 2017; (b) GOES-16OB magnetic field measurement minus model field for 22 Dec 2017.

Another indication that the variation with time of day presented in Figure 1 is mostly due to a variation in the GOES-16 data is found in comparing the GOES-16OB data with GOES-14OB data on the same day., The comparison in Figure 3 of GOES-16OB with GOES-14OB data on the same day is as the comparison in Figure 1. For Figure 3, the model field was applied to both satellite data sets to compensate for the difference in longitude. The minimum to maximum variation occurs from a time near 00 to 03 UT to a time near 21 to 24 UT. This commonality indicates that there is a significant variation in the GOES-16OB measurements as function of time of day for this date.

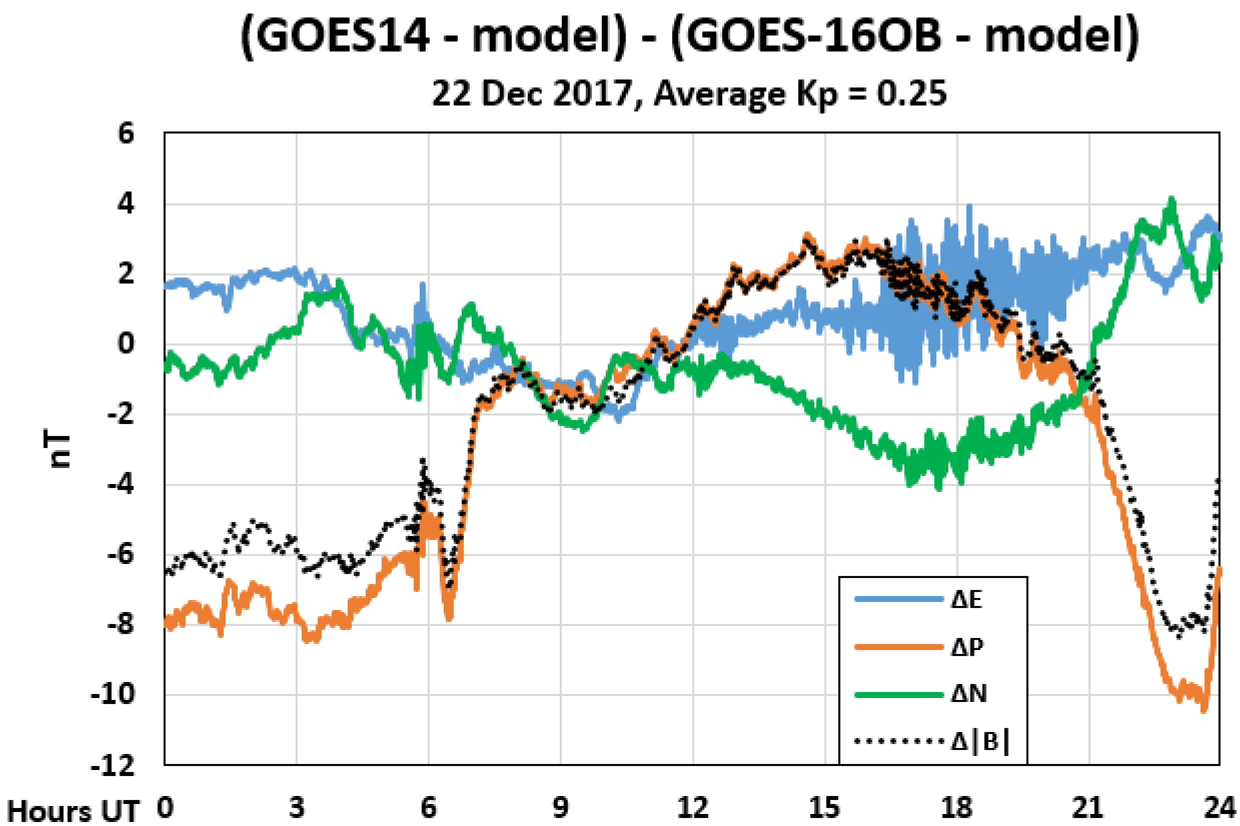


Figure 3 Difference between the magnetic field measured by GOES-14 outboard magnetometer and the GOES-16 outboard magnetometer on 22 Dec 2017. The time of the measurement is at the same time as the measurement shown in Figure 1. The model magnetic field has been subtracted from both sets of measurement to compensate for the difference in longitude.

To further demonstrate the GOES-16OB diurnal pattern, the difference between the GOES-16OB and the GOES-14OB magnetic field data vs. time of day for all quiet periods (Kp ≤ 1+) from the January 2018 to the end of the GOES-14 data is shown in Figure 4. Only the error bars for the P-component are shown to avoid clutter and because the P-component is the largest component of the magnetic field vector. The size of the error for the E and N components are similar. Errors in the model field accounts for a small, but unresolved portion of the difference between the patterns in Figures 3 and 4 versus the patterns in Figure 1. The largest variation in Figure 1, 2b and 3 is in the P component. The diurnal pattern in Figure 4 is like the pattern in

Figure 1 but the range throughout the day is less. The size of the diurnal variation is a function of season. Based on the range of the P-component difference, the diurnal pattern is worst in the December – January period when the average P-component range is 9.5 nT and best in the May - June period when the average P-component range is 4.2 nT.

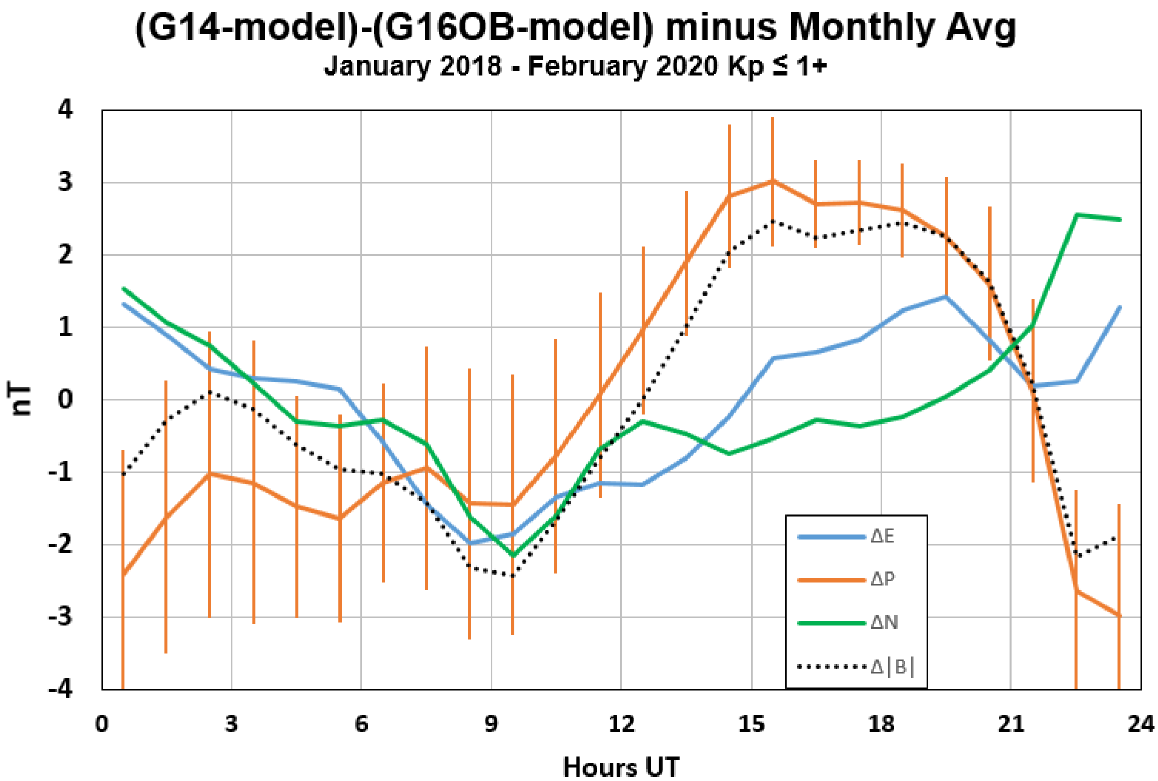


Figure 4 Difference between the magnetic field measured by GOES-14 outboard magnetometer and the GOES-16 outboard magnetometer during quiet periods between January 2018 and February 2020.

The GOES-16OB to GOES-14OB comparison was used to investigate the effect of season on the diurnal variations. Figures 5 and 6 show four monthly averages of the diurnal variations of the measurements versus the TS04 model during quiet time for GOES-16OB and GOES-14OB respectively. The months were selected to represent four seasons. The diurnal patterns are slightly different for each season and for each satellite. The errors in the GOES-14OB vs. model field data shown in Figure 6 may be due to GOES-14OB data or the model field or both.

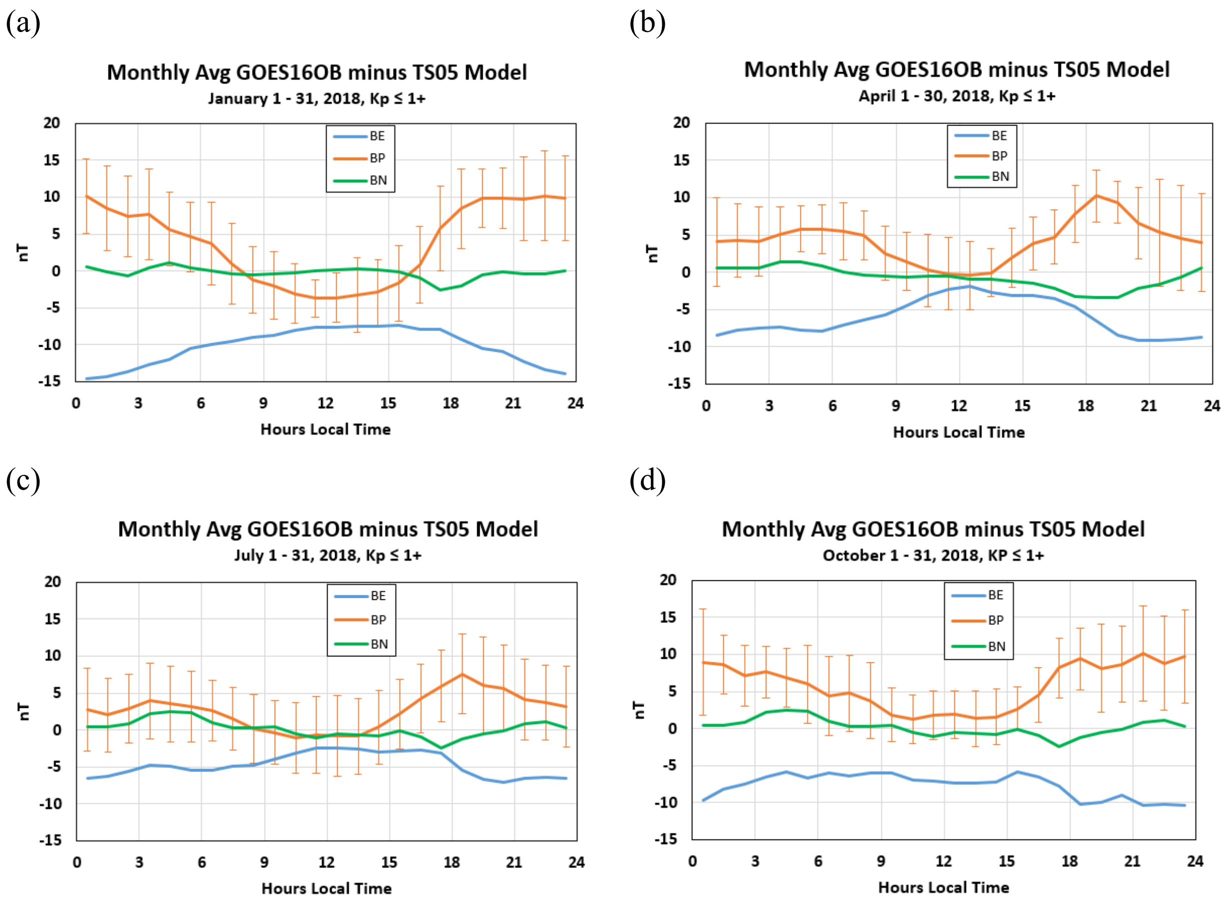


Figure 5 Local time variations of the GOES-16 outboard for quiet-periods ($Kp \leq 1+$ for (a) January 2018, April 2018, July 2018 and October 2018. Each data point is the average for all days in a month for the hourly averages of difference between the GOES-16 outboard magnetic field measurements and the TS05 model field.

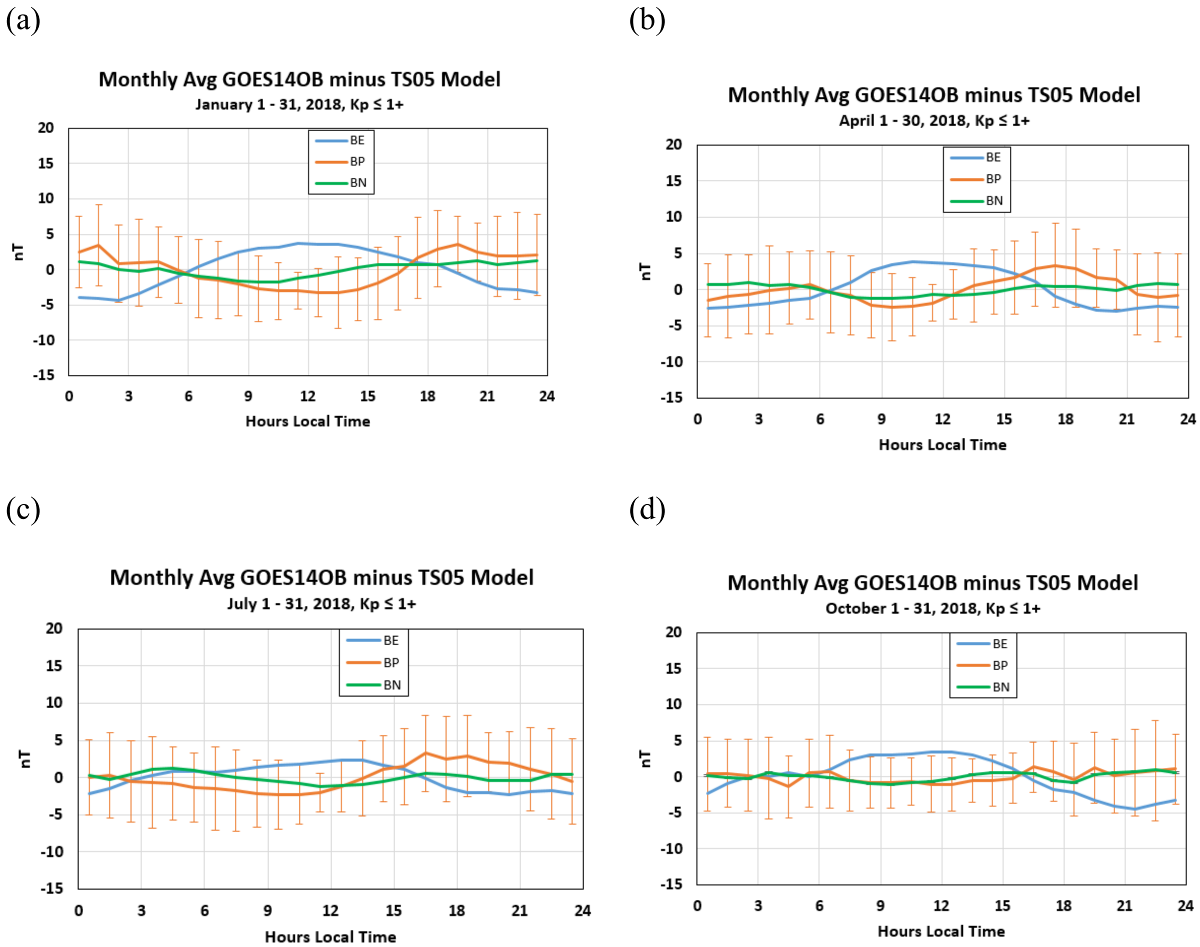


Figure 6 Monthly average of the diurnal variation of the GOES-14OB magnetic field measurements minus the TS05 model magnetic field for Kp ≤ 1+ for (a) January 2018, April 2018, July 2018 and October 2018.

The patterns in Figures 5 and 6 repeat from year to year but that repetition is not shown here. An attempt was made by the GOES-R team to model the GOES-16OB diurnal variations based on the angle between the instrument and the Sun, but the results were not satisfactory enough to be applied to the operational GOES-16OB data.

4.2 Diurnal Variations of GOES-17 Magnetometer Data

An examination of GOES-17 data was performed to assess diurnal variations. When GOES-17 was moved into the operational GOES-West position (137.2° W), GOES-15 was moved into an alternate GOES-West position (128° West). The closeness of GOES-17 and GOES-15 reduces the differences in the comparisons because the model fields at the two satellite locations were better correlated. The differences in the quiet-period (Kp ≤ 1+) measurements made by each satellite are shown in Figure 7 for four months to represent four seasons. The average diurnal variation of GOES-17OB to GOES-15OB is less than ± 1 nT. There is a change in the diurnal variation with season as shown in Figure 7 but it is so small that it may be due to the model and/or statistical variations instead of any variations caused by the instrument on either satellite.

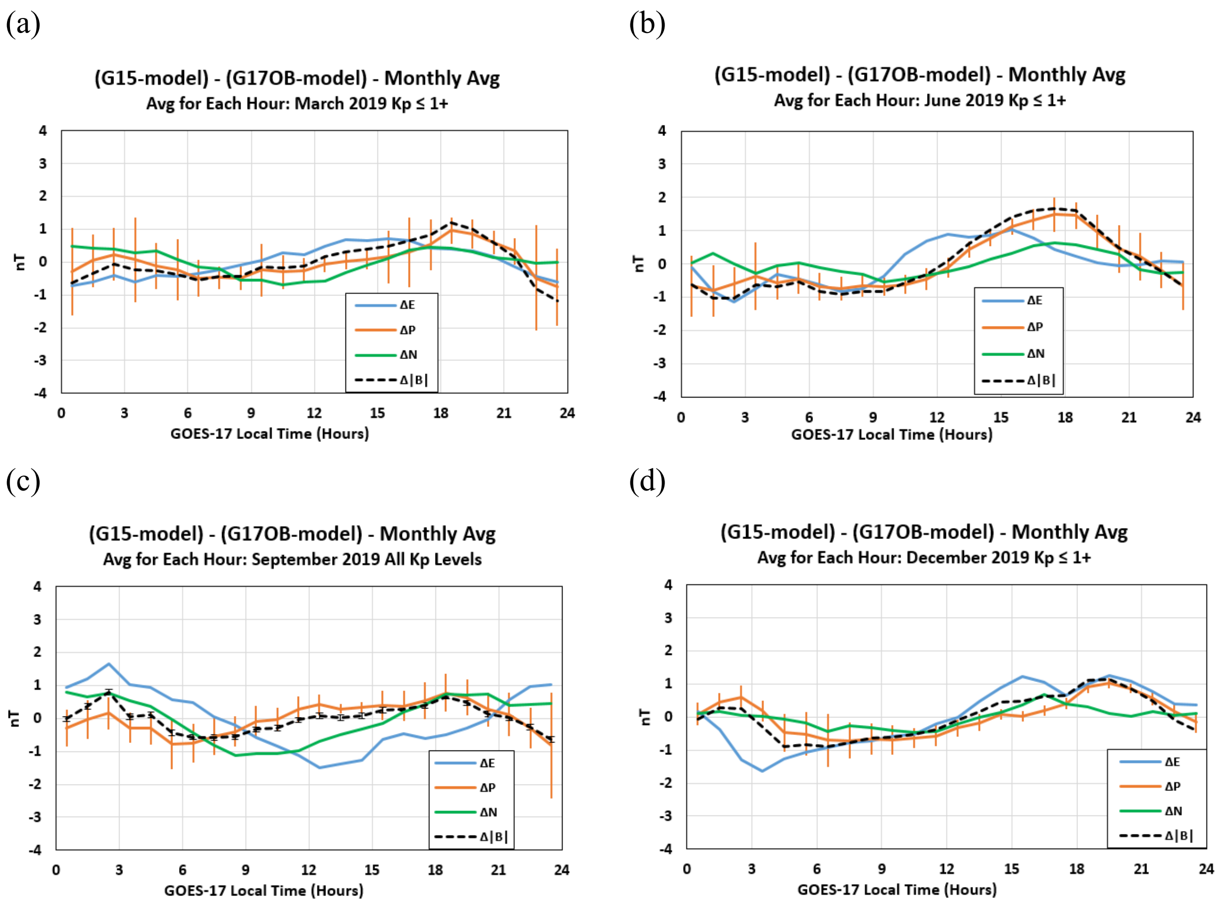


Figure 7 The monthly averages of difference between the magnetic field measured by GOES15 and GOES-17OB for each hour of the day with the model field removed for Kp ≤ 1+ for the months of (a) March 2019, (b) June 2019, (c) September 2019 and (d) December 2019. The average values for the month have been removed to separate diurnal variations from longer term variations.

Figure 8 shows the diurnal variations in the comparisons between the GOES-17OB data and the GOES-14OB for quiet-periods (Kp ≤ 1+) from for four months in 2019 to show the seasonal variations. The diurnal variations and the standard deviations shown in Figure 8 for the P-component are much larger than those shown in Figure 7 for the P-component for GOES-17OB vs. GOES-15OB. In turn, the values shown in Figure 8 are smaller than the values shown in Figure 4 for GOES-16OB vs. GOES-14OB. Since the GOES-17OB data compared well to the GOES-15OB data, the larger range of the variations in Figure 8 must be due to the GOES-14OB data or the model or both.

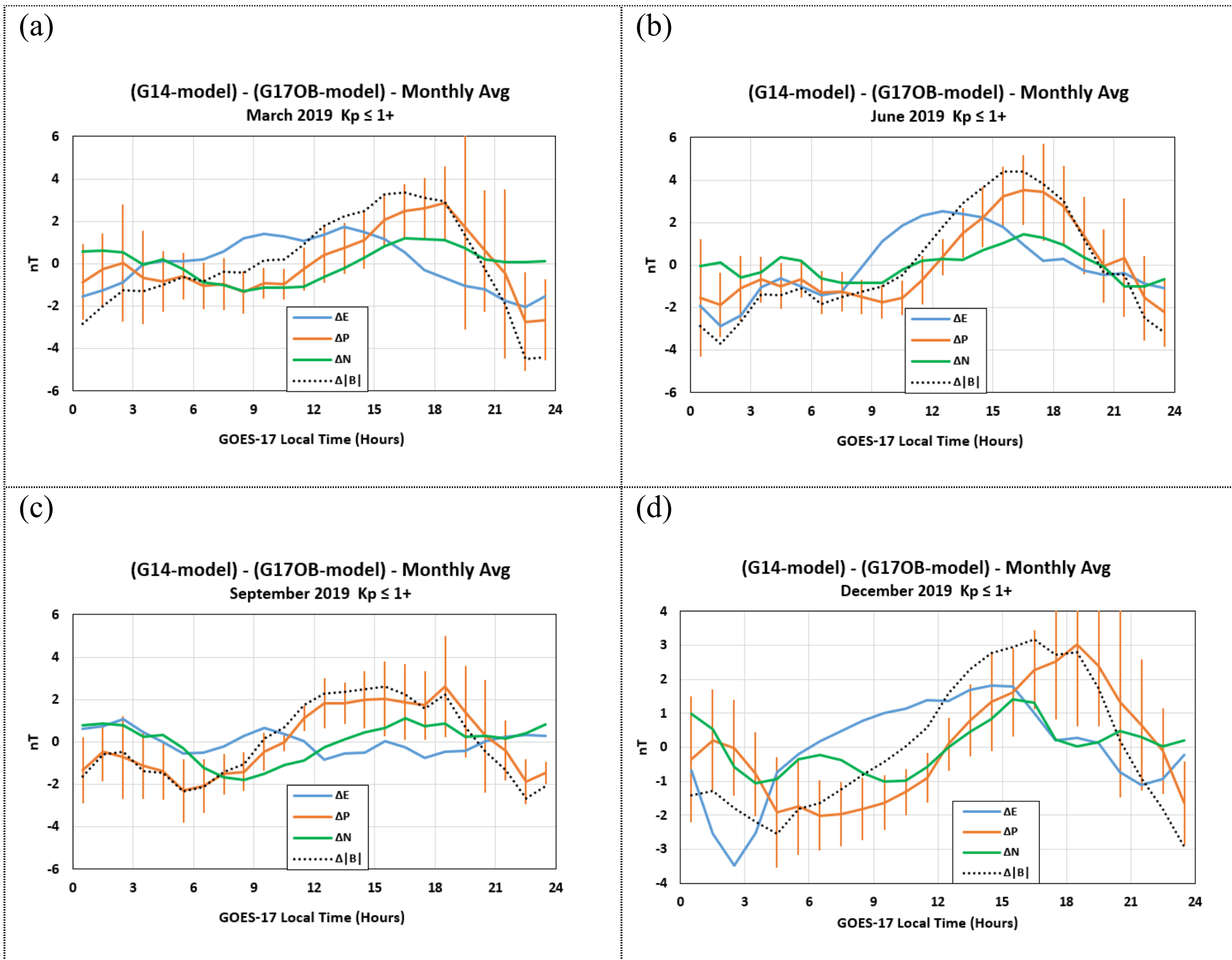


Figure 8 The monthly averages of difference between the magnetic field measured by GOES14 and GOES-17OB for each hour of the day with the model field removed for Kp ≤ 1+ for the months of (a) March 2019, (b) June 2019, (c) September 2019 and (d) December 2019. The average values for the month have been removed to separate diurnal variations from longer term variations.

5 Long-term Trends of GOES-16OB and GOES-17OB Magnetometer Data

By comparing GOES-16OB or GOES-17OB magnetic field data to magnetic field data from other satellites, we can obtain an estimate of the error in the zero level of each component for each satellite. The comparisons are made using daily averages of the differences between the two satellites. Because the diurnal variations change by very small amounts from day to day, the daily averages eliminate the effect of the diurnal variations. In most cases, the daily averages are compiled into monthly averages for display of the comparisons. As mentioned before, the model field must be used to account for differences in longitude and its usage can introduce unknown errors in the inter-satellite comparisons, but the model has been applied uniformly. Table 2 provides a summary of the inter-satellite comparisons. Use of quiet-period (Kp ≤ 1+) measurements reduces the statistical error of the comparisons but changes the average differences by a small amount.

Table 2 Average, median and values at the 15.9/84.1 percentile and 0.1 and 99.9 percentile levels of the daily averages of the difference between magnetic field measurements at two GOES satellites after using TS05 model to remove longitudinal differences. (NM=Not meaningful.)

GOES comparisons Data Period (	GOES-15 (128° W) minus GOES-17 (137.2° W) Feb 2019 - Feb 2020	GOES-14 (105° W) minus GOES-17 (137.2° W) Feb 2019 - Feb 2020	GOES-16 (75.2° W) minus GOES-17 (137.2° W) Feb 2019 - Sep 2020	GOES-14 (105° W) minus GOES-16 (75.2° W) Dec 2017 - Feb 2020	GOES-15 (137.2° W /128° W) minus GOES-16 (75.2° W) Dec 2017 – Nov 2018 / Nov 2018 - Feb 2020	GOES-13 (74.6° W) minus GOES-16 (75.2° W) Dec 12 - 30, 2017
<ΔE> Mean ΔE	0.83 0.82	-4.27 -3.99	-5.48 -5.46	0.83 0.89	5.84 5.98	3.53 3.49
<ΔP> Mean ΔP	0.10 0.03	-0.03 -0.16	0.86 0.76	-1.27 -1.28	-1.24 -1.13	-4.57 -4.65
<ΔN> Mean ΔN	-0.07 -0.06	-1.22 -1.27	0.03 -0.09	-1.10 -1.06	0.06 0.11	-0.84 -0.83
<Δ|B|> Mean Δ|B|	0.08 0.00	-2.20 -2.26	-2.04 -2.20	-0.67 -0.63	1.43 1.55	-3.02 -3.21
ΔE 15.9/84.1 Percentile	-0.50 2.00	-6.65 -2.17	-7.49 -3.50	-0.23 1.79	3.98 7.70	3.41 3.62
ΔP 15.9/84.1 Percentile	-0.32 0.56	-1.05 0.97	-0.71 2.31	-2.28 -0.24	-2.77 0.31	-4.24 -3.70
ΔN 15.9/84.1 Percentile	-0.30 0.13	-1.76 -0.71	-0.94 0.93	-1.92 -0.26	-0.94 1.02	-0.90 -0.77
Δ|B| 15.9/84.1 Percentile	-0.57 0.73	-3.98 -0.44	-3.99 0.00	-1.74 0.35	-0.52 3.42	-3.44 -2.33
ΔE 0.1/99.9 Percentile	-2.48 4.01	-10.24 2.92	-11.92 1.65	-4.25 6.04	-9.50 11.82	NM
ΔP 0.1/99.9 Percentile	-1.91 2.05	-3.30 6.11	-3.78 9.99	-7.57 2.80	-9.30 3.19	NM
ΔN 0.1/99.9 Percentile	-1.01 1.45	-2.66 3.16	-4.17 7.90	-4.84 2.12	-6.31 4.04	NM
Δ|B| 0.1/99.9 Percentile	-1.77 3.40	-7.70 4.00	-8.26 7.79	-6.25 4.33	-6.69 6.92	NM

5.1 Long-term Trend of GOES-16OB Magnetometer Data

The monthly averages of the comparisons of the GOES-16OB magnetic field data to GOES-14OB and GOES-15OB are shown in Figures 9 and 10 by solid lines for each component.

The GOES-16OB to GOES-14OB comparisons are for the period from December 2017 to February 2020 while the comparison of GOES-16OB to GOES-15OB covers both the period of December 2017 to November 2018, when GOES-15 was in the GOES-West position, and the period from November 2018 to February 2020, when GOES-15 was in the alternate GOES-West position.

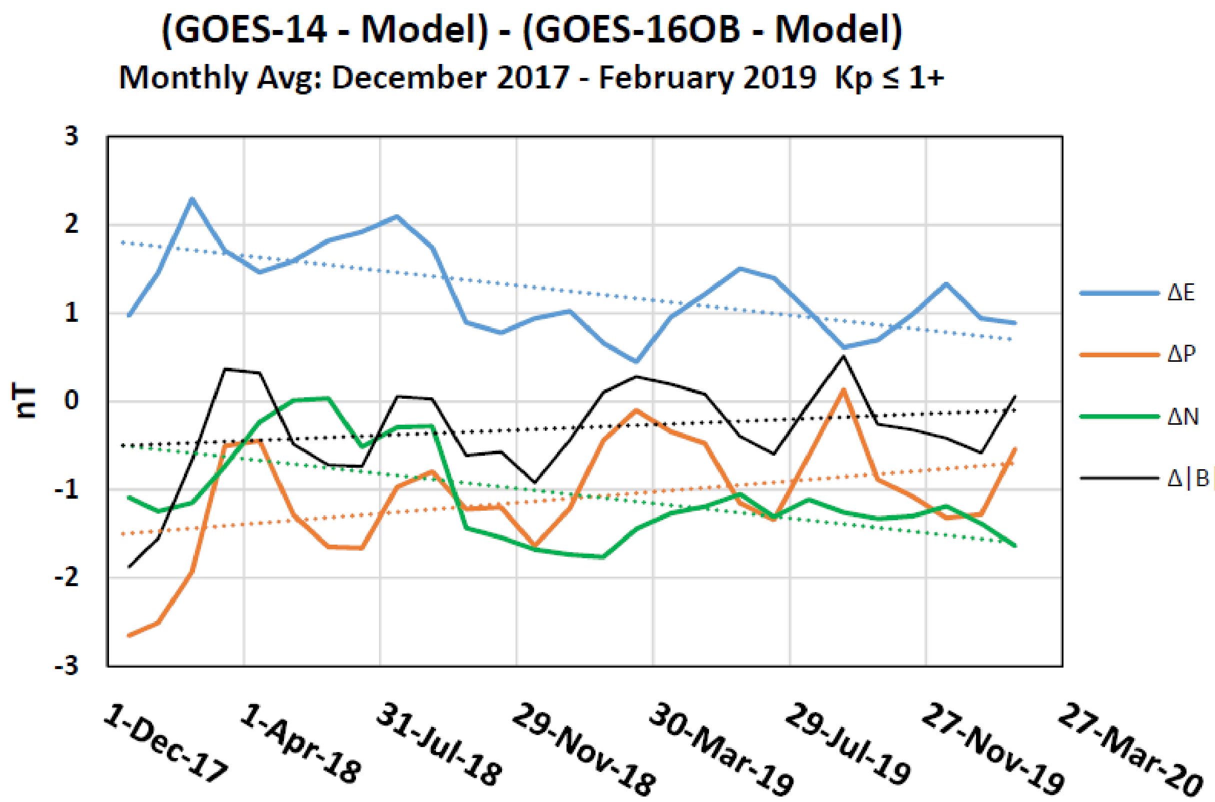


Figure 9 Solid lines are the monthly averages of the difference between the GOES-14OB and GOES-16OB measurement with adjustments using the model field. The dotted lines are the linear fit to the monthly averages.

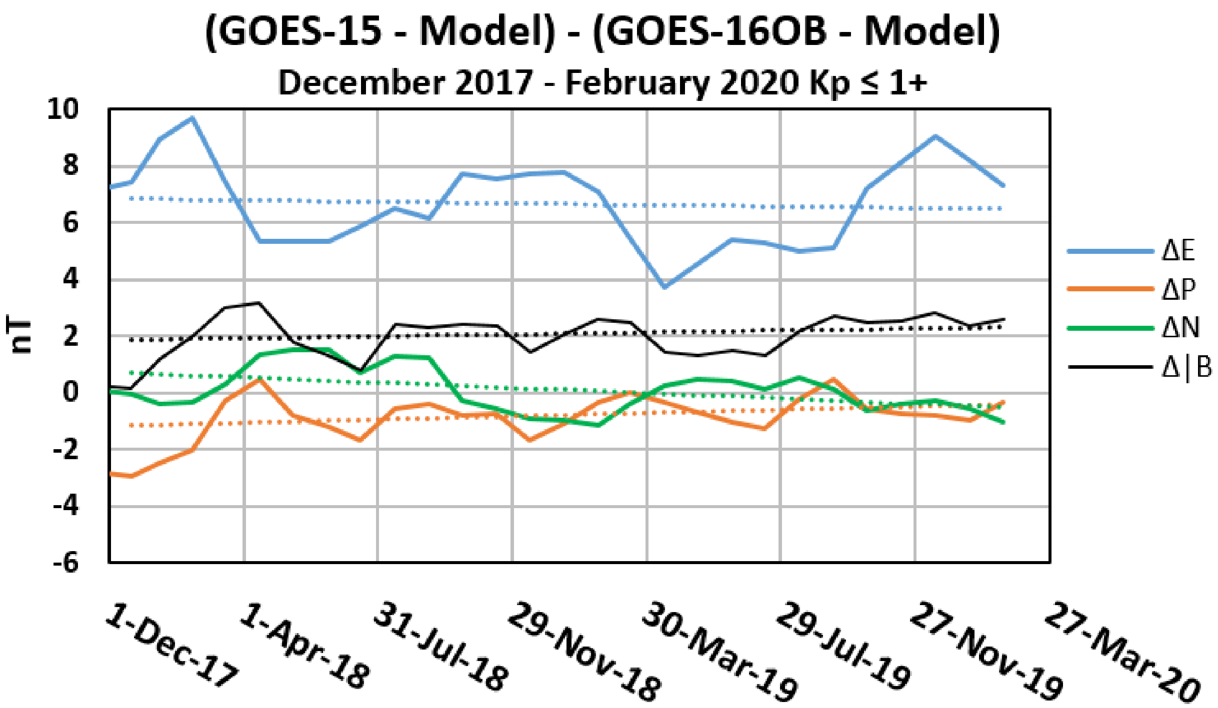


Figure 10 Solid lines are the monthly averages of the difference between the GOES-15OB and GOES-16OB measurement with adjustments using the model field. The dotted lines are the linear fit to the monthly averages.

Linear regression was used to fit the monthly averages for each component of the magnetic field and for the field magnitude, shown as dotted lines in Figures 9 and 10. The linear fits to assess accuracy for GOES-16OB vs. GOES-14OB E, P and N components and the field magnitude change by -0.4, 0.4, -0.4 and 0.3 nT/year. The linear fits for GOES-16OB vs. GOES-15OB E, P, N magnitude differences change by -0.2, 0.5, -0.4 and 0.4 nT/year. If the assumption is made that all the changes in the differences with time are due to the GOES-16OB magnetometer, these fits to the change rates are small enough to consider GOES-16OB to be stable and will continue to be stable until the end of the GOES-16 lifetime. It is likely that the GOES-14OB and GOES-15OB measurements make a small contribution to these small rates of change. That implies that the GOES-14OB and GOES-15OB measurements are also stable.

In Figures 9 and 10, there are oscillations in the monthly averaged differences which we cannot explain. An investigation of the cause is beyond the scope of this study. It should also be noted that the differences in the E- component is greater for GOES-16OB vs. GOES-15OB than for GOES-16OB vs. GOES-14OB. It is likely that this increase is due to the greater difference in longitude from GOES-16 to GOES-15 than from GOES-16 to GOES-14.

Statistics parameters from the model adjusted differences of GOES-16OB vs. GOES-14OB and vs. GOES-15OB were computed from all the daily averages and are given in Table 2. The daily averages for the comparisons were compiled into histograms (not shown here) which indicated that the differences are not distributed like a Gaussian distribution. In Table 2 both the average value (mean) and the median (50 percentile) values are shown. The 15.9 and 84.1 percentile values in the distribution are shown in lieu of the standard deviation (1σ) values and the 0.1 and 99.9 percentile values are shown in lieu of the 3σ values. The 15.9 and 84.1

percentile (approximately ±1σ) variations about the mean of GOES-16OB vs. GOES-14OB and GOES-16OB vs. GOES-15OB are within ± 3 nT of the mean values.

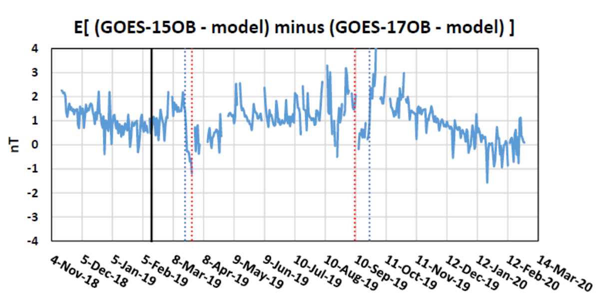
5.2 Long-term Trend of GOES-17OB Magnetometer Data

Starting with the time when the GOES-17 satellite was moved into the GOES-West (operational) location, the GOES-17 magnetic field data were compared with GOES-14OB magnetometer data in the GOES storage location and with GOES-15OB magnetometer data in the alternate GOES-West location. The GOES-15 satellite was closer to GOES-17 than GOES-14 or GOES-15 was to GOES-16. The closeness of GOES-17 and GOES-15 reduced the differences in the comparisons due to satellite separation.

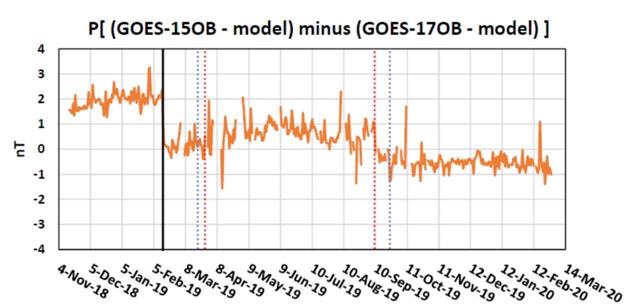
The GOES-17 satellite executes a yaw-flip maneuver every six months. As mentioned above, a yaw-flip is a 180° rotation of the satellite about the Earth-pointing (spacecraft's X) axis. This provides a calibration-like maneuver which can be used to determine the zero offset in the P and N field components. A full set of calibration maneuvers is undertaken for each GOES satellite only during the check-out phase. The analysis of the effect of yaw flips is shown below. The GOES-15 satellite also executes a yaw-flip every six months on days which are a few days apart from the days when a GOES-17 yaw-flip is executed.

The daily averages of all one-minute differences between GOES-17OB and GOES-15OB magnetic field from November 14, 2918 to February 29, 2020 with the model field compensating for the longitude difference are shown in Figure 11. There are gaps in these data due to gaps in the input data used to compute the model field. The black vertical line in each frame indicates the day (February 14, 2019) when the GOES-17OB temperature setting was changed from 10° C to 20° C. The red, dashed vertical lines indicate the days when the GOES-17 satellite executed a yaw-flip. The blue, dashed vertical lines indicate the days when the GOE-15 satellite executed a yaw-flip. At each of the days marked by vertical lines, a shift in the difference values occurs. These shifts are due to an error in the zero level. It was initially assumed that the GOES-17OB error was due to a calibration error. As explained below, this assumption later determined to be wrong.

(a)



(b)



(c)

(d)

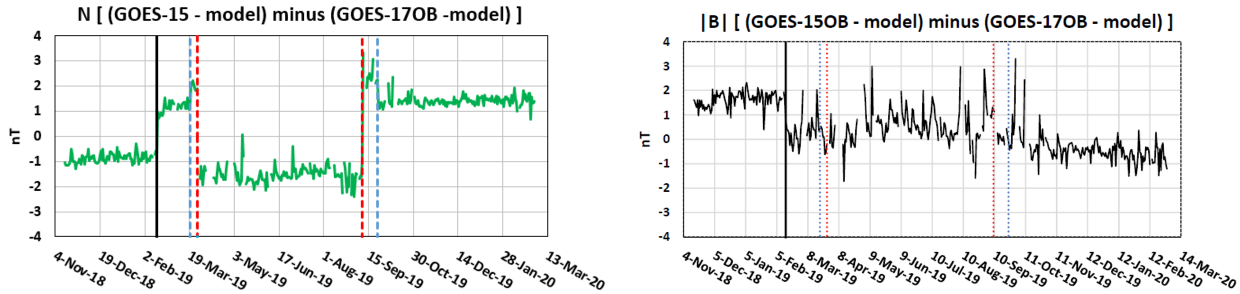


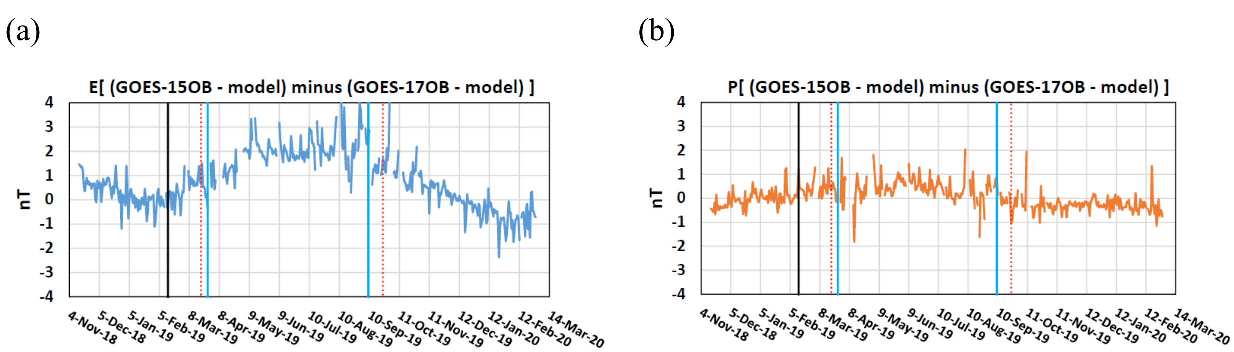
Figure 11 Daily averages of the comparison of GOES-15OB to the GOES-17OB magnetometer data using the GOES-17 zero levels determined by calibration maneuvers.

Analysis of the GOES-17OB to GOES-15OB differences determined an error of the GOES-17OB zero offset for the P and N components of -0.25 and 1.82 nT respectively. These corrections were implemented in the ground processing at 1902 UTC on February 22, 2021. For archived data processed before this date, the correction values should be subtracted from the archival data when the GOES-17 satellite is in the upright orientation (March to September) and added to the measurements when the spacecraft is in the inverted orientation (September to March).

An examination of the differences from before to after the GOES-15 yaw-flips indicated a mismatch in the differences in the E- and N-components. The N-component mismatch are due to errors in the GOES-15OB zero offset of -0.8 nT. There is a mismatch in the E-component 0.5 nT. The yaw-flip related change in the E-component was not expected because the yaw-flip rotations are about the E-axis. The change is consistent for all the GOES-15 yaw flips examined, which suggests that the E-component bias is dependent on the orientation of the magnetometer to the spacecraft.

A comparison of data from the GOES-17IB (inboard) magnetometer to the GOES-15OB magnetic field data was also performed but not shown here. An examination of these differences before and after yaw flips determined that the zero offset for the GOES-17IB magnetometer data should be corrected by 0.5 nT in the N-component, and the P component did not need a correction of the zero offset. This change was also applied in GOES-17 ground processing on February 22, 2021.

Figure 12 shows the difference between the GOES-15OB and GOES-17OB data after the corrected zero offsets were used in offline processing of both data sets. The mean and the 15.9 and 84.1 percentile differences between the GOES-17OB and the GOES-15OB after applying the zero offset corrections are given in Table 2. The 15.9 and 84.1percentile differences differ from the median difference for the P and N components by 0.5 nT or less. There is a long-term oscillation in the E-component of approximately 3 nT from minimum to maximum difference which is apparently due to season. We have not determined the source of this long-term oscillation.



(c) (d)

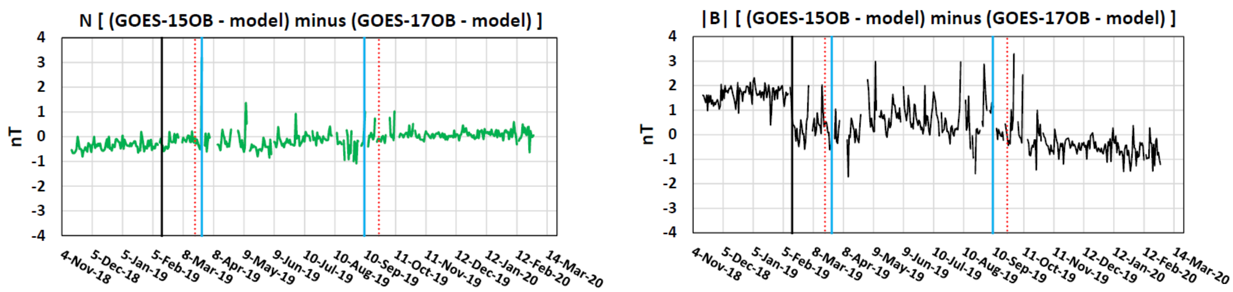


Figure 12 Daily averages of the comparison of GOES-15OB to the GOES-17OB magnetic field data using the GOES-15 and GOES-17 zero levels corrections determined from the first two yaw-flips applied.

The differences between the zero-offset corrected GOES-17OB daily average magnetic field measurements and the GOES-14OB measurements were computed. This comparison is another investigation of any long-term trends in the GOES-17OB data. The results are shown in Figure 13. The most notable difference between the results shown in Figure 12 and 13 is the increase in the day-to-day variations due to GOES-14 being farther from GOES-17 than GOES-15. The increase is due to errors in the model field and to local disturbances that cannot be accounted for by the model field. As shown in Table 2, the 15.9 and 84.1percentile of the GOES-17OB to GOES-14OB difference for the P and N components are 1.2 nT or less from the mean value. For the E-component of the GOES-17OB vs. GOES-14OB differences, there is a seasonal oscillation of approximately 3 nT from the minimum to the maximum level. This E-component oscillation is similar to the oscillation for the GOES-17OB to GOES-15OB comparison.

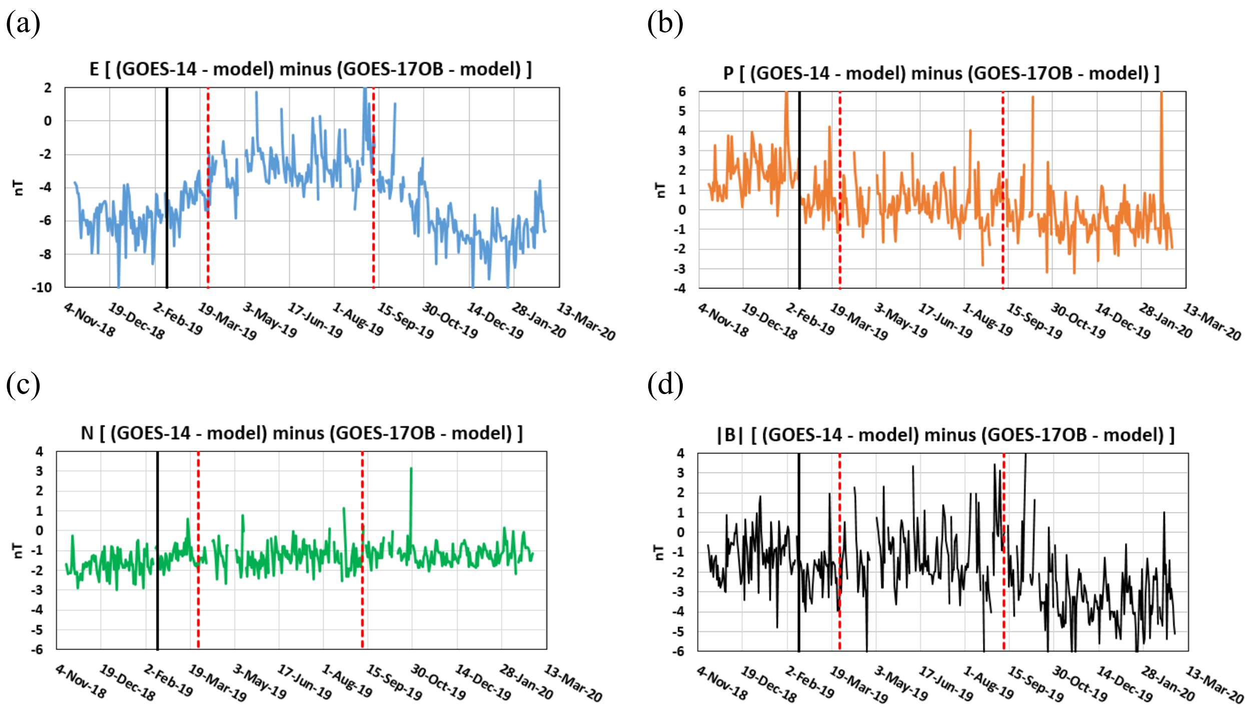


Figure 13 Comparison of the daily averages of the GOES-14OB to the GOES-17OB magnetic field data with the GOES-17OB zero levels determined from the first two yaw-flips applied.

The differences between the zero-offset corrected GOES-17OB daily average magnetic field measurements and the GOES-16OB measurements were computed. The results are shown in Figure 14. The method of comparison was the same as the comparison of the GOES-17OB data with the GOES-15OB and GOES-14OB data. Because GOES-16 was farther from GOES-17 than GOES-14 or GOES-15, the day-to-day variations of the differences were greater than the GOES-17OB-to-GOES-14OB or GOES-15 day-to-day variations. The means and 15.9 and 84.1percentile values of the differences from the February 2019 to September 2020 are shown in Table 2. To dampen the daily variation in Figure 14 to emphasize the long-term variation, a seven-day running average of the daily comparisons was applied to the data plotted. Because the GOES-16 data continued to be available after the availability of the GOES-14 and GOES-15 data stopped, the comparison was extended to mid-November, 2022. The yearly oscillation of the E-component difference which occurs in other comparisons is evident in this comparison.

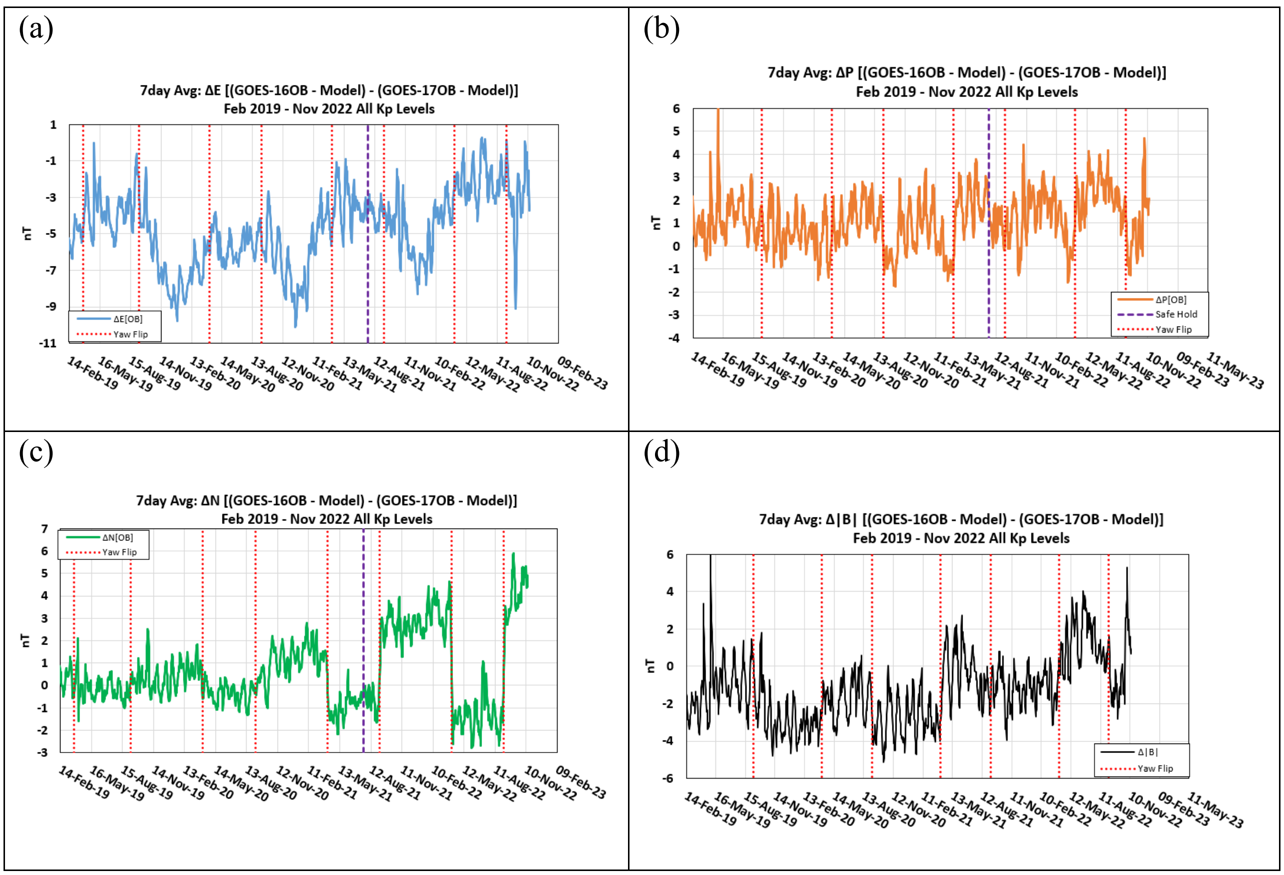


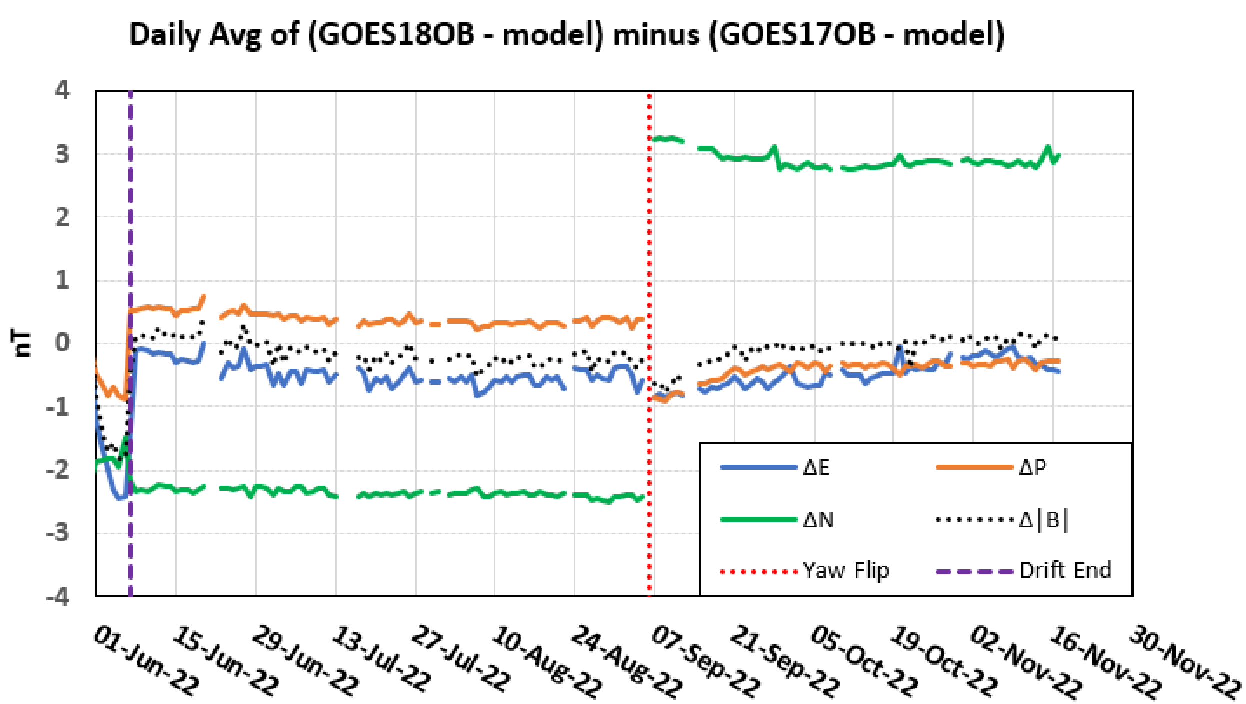
Figure 14 Comparison of the magnetic field daily averages of GOES-16OB to GOES-17OB with GOES-17OB zero levels determined from the first two yaw-flips applied.

By comparing the data shown in Figure 14 up to March 2020 with the data shown in Figure 11, the correction to the GOES-17 zero-offset was an effective change. However, as the data proceeded beyond March 2020, there is an increasing offset in the N-component revealed by each yaw-flip. The correction implemented in the GOES-17 data based on data up to March 2020 was assumed to be due to a calibration error which would not change. The data shows this assumption was not valid.

6 GOES-17 vs GOES-18

In May 2022 the GOES-18 satellite was drifted from the check-out longitude toward the GOES-17 longitude. From June 8, 2022 to the January 2023, the two satellite were within 0.2° of longitude of each other. This made it possible to compare the two data sets without the use of a model field. Figure 15a shows the comparison of the previously mentioned zero-offset corrected GOES-17OB data to the GOES-18OB data, with the calibration values from the calibration maneuver applied. Because there is a change in the comparison when the GOES-17 yaw-flip occurs on September 6, 2022, the change can be assigned to an error in the GOES-17OB zero offset. This error is -0.6 nT in the P component and 2.8 nT in the N-component. Figure 15b shows the comparison with the additional error applied to the GOES-17OB data. The result is that GOES-17OB and GOES-18OB agree within 1 nT in all components and the total field. For the short period from June to November 2022, there is no trend is the comparison.

(a)



(b)

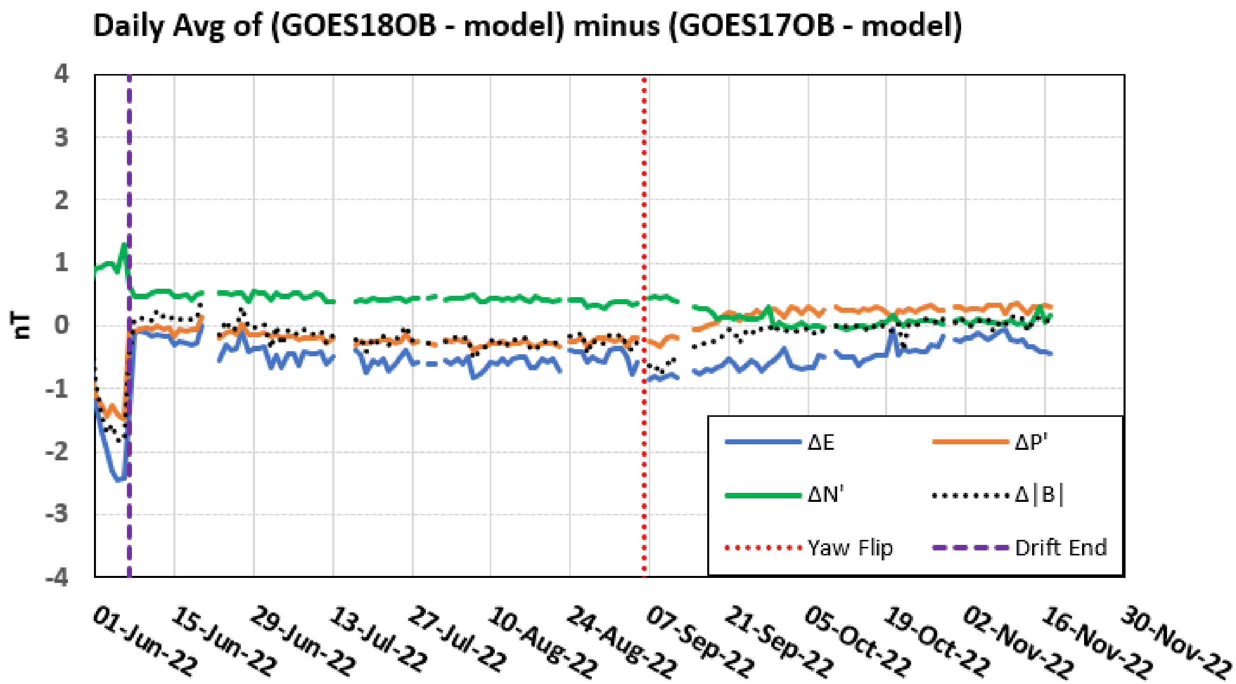


Figure 15 Comparison of the magnetic field daily averages of the GOES-18OB to GOES-17OB (a) with the previously determined correction applied to GOES-17OB and (b) with the additional correction applied to GOES-17OB data.

7 GOES-13 vs. GOES-15

A comparison of the GOES-15OB to GOES-13OB magnetic field data was performed to demonstrate that usage of the GOES-NOP data is appropriate for determining the long-term stability of the GOES-16OB and GOES-17OB magnetic field data. We have compared the GOES-13OB to the GOES-15OB magnetic field data in the same manner that the GOES-16OB and GOES-17OB magnetic field data were compared to GOES-13OB, GOES-14OB and GOES-15OB magnetic field data. The monthly averages of the comparisons are shown in Figure 16 for the period January 2011 to December 2017. The GOES-15OB data were corrected by the amount shown in Table 3 due to the analysis of the 2019 yaw flip data. Dashed lines in Figure 16 shows a linear regression for each component computed from the daily averages. The linear regression lines change by 0.083, 0.023, and -0.018 and -0.021 nT/year for the E, P and N coordinates and the field magnitude. From this we conclude that measurements by both GOES-13OB and GOES-15OB did not change enough during the span of seven years to affect our conclusions. The differences on January 1, 2011 were -3.02, -1.88, -0.99 and -2.26 nT. Given that GOES-13OB and 15OB agree to ~3 nT/axis or less throughout the 7-year span, and that the zero offsets (biases) were determined during each satellite's post launch testing and checkout, the results suggest that the maximum error in the zero offset of either magnetometer is less than ±3 nT/axis.

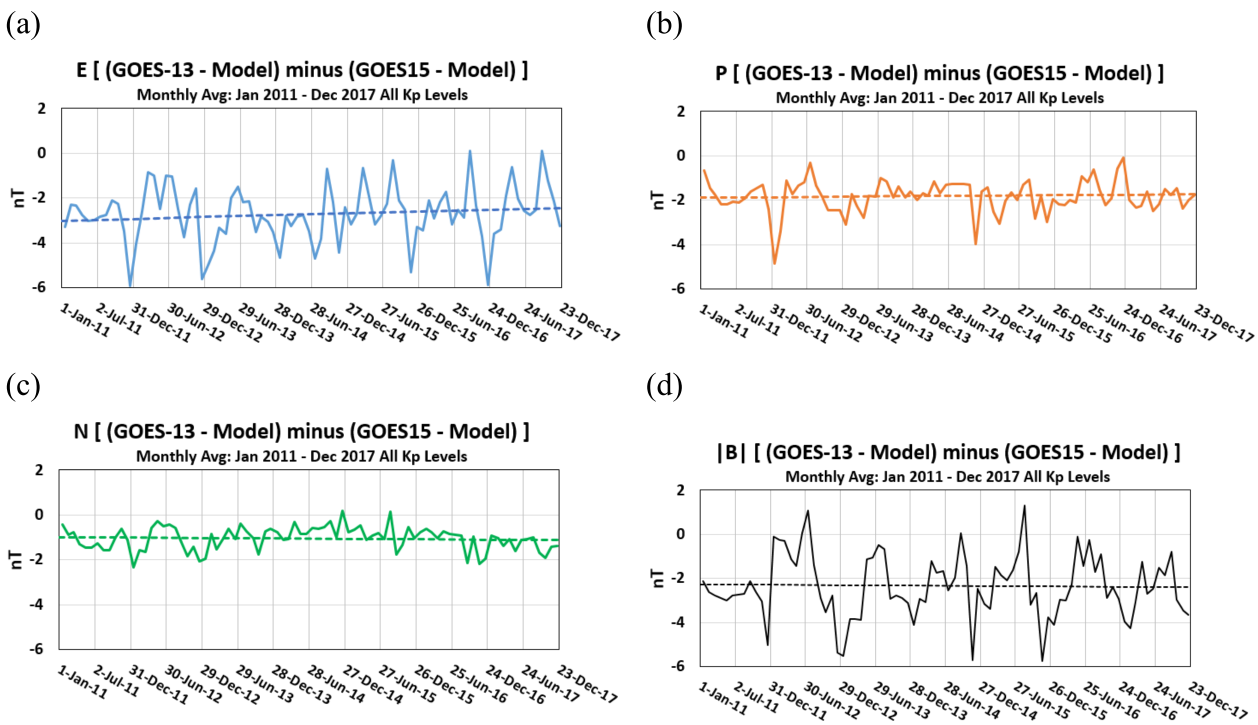


Figure 16 The solid lines are the monthly averages computed from the daily averages of the simultaneous differences between the GOES-13 and the GOES-15 magnetic field measurement. The dashed lines are the linear fits to the daily average differences for each of the magnetic field components and the field magnitude.

Individual monthly averages of the comparisons diverge from the linear regression by much more than ± 3 nT especially in the E component. Part of the cause for these larger variations is the usage of data during all geomagnetic conditions and not just quiet conditions, which affects the accuracy of the model subtraction. However, that does not fully explain the larger variations. There is also an oscillation of the E component in Figure 16 over what appears to be an annual scale. A similar variation of the E component is shown in Figures 12, 13, and 13. A detailed examination of this variation is beyond the scope of this study. A more detailed analysis of the GOES-NOP data will be given in the future.

8 Conclusions

In this study, we have assessed the accuracy of the geomagnetic field measurements made by the GOES-16 and GOES-17 outboard magnetometers by comparing these measurements with simultaneous measurements made by magnetometers on GOES-NOP series of satellites (GOES-13OB, -14OB, and GOES-15OB) and GOES-18. The assessments were made for the average diurnal measurements and for the daily averages over periods of as many months as possible. The usage of averages eliminates high-frequency magnetic field fluctuations for examining the bias. The TS05 magnetic field model was used to minimize differences due to longitudinal separation of each pair of satellite measurements. The TS05 model is a good but not a perfect representation of the magnetic field. The usage of long-term averages minimizes the differences due to imperfections in the model field. The results of these inter- satellite comparisons are shown in Table 2. As expected, the best comparisons are from the satellites closest to GOES-16 or GOES-17.

The best comparison for the GOES-16OB measurement is with the GOES-14OB measurements. The two satellites were only 2 hours of local time apart. The average diurnal variations for each of the E, P and N components of the magnetic field vector are ± 3 nT or less about the monthly mean. The difference between the monthly averages for each of the components is ± 2 nT or less with a small shift in the values over the period studied. The 3-σ equivalent spread of the average diurnal variations are ±6 nT or less over two years.

GOES-16 magnetometer hardware and installation shortfalls were addressed in GOES-17 magnetometer hardware and installation, reflected in the improved performance of GOES-17 magnetometer. The best long-term comparison for GOES-17OB measurements was with GOES-15OB measurements over 12.5 months (February 2019 – February 2020) when the satellites were separated by half an hour of local time. The average diurnal variations for each of the E, P and N components of the magnetic field vector are ± 1.5 nT or less about the monthly mean. The mean of the daily- averaged differences for the E and P components and the field magnitude is ± 1.0 nT with a 3-σ equivalent spread of the values of ±3.4 nT or less. The E-component of the differences oscillated about an average of ~ 1.0 by ± 1.5 nT with a period of 12 months. The source of the oscillation was not determined, but may be due to factors not related to data from either satellite, such as systematic errors in the TS05 model.

After adjusting for a change in the zero-offset of GOES-17OB, the GOES-17OB measurement matched the GOES-18 within ± 1 nT when the two spacecraft were separated by 0.2° of longitude (June – November 2022). The data from the improved GOES-18 magnetometers reflects improved stability over GOES-17 magnetometer with accuracy of < 1.0 nT.

Comparisons over seven years of monthly average differences between the GOES-13 and GOES-15 magnetic field measurements showed less than a 3 nT change over the lifetime. This indicates that the usage of the previous generation of instruments is a valid method for determining the limits of the measurements made by the new generation of instruments.

Acknowledgments

We wish to acknowledge and thank the GOES-R Series Program Office for support during the study. GOES-R series data was made available through the GOES-R Ground Segment. For the MIT LL authors, this material is based upon work supported by the National Oceanic and Atmospheric Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the MIT LL authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration. For the NCEI authors, the views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, or other U.S. Government position, policy, or decision.

Data and Software Availability Statement

GOES-16, GOES-17 and GOES-18 magnetometer L1b data are available at NOAA's Comprehensive Large Array-data Stewardship System (CLASS) https://www.class.noaa.gov/ and National Centers for Environmental Information, Boulder, CO, USA (NCEI) https://www.ngdc.noaa.gov/stp/satellite/goes-r.html. GOES-13, GOES-14 and GOES-15 calibrated data are available at https://satdat.ngdc.noaa.gov/sem/goes/data/full/.

Data needed as input to the TS05 model have been acquired from the NASA Space Physics Data Facility OMNIWEB (https://omniweb.gsfc.nasa.gov/). The TS05 model field was computed using the IRFU-MATLAB analysis package available at https://github.com/irfu/irfu-matlab and developed by Institute of Research into the Fundamental Laws of the Universe.

References

Andreeva, V. A., Tsyganenko, N. A. (2018). Empirical modeling of the quiet and storm time geosynchronous magnetic field. Space Weather, 16, 16–36, https://doi.org/10.1002/2017SW001684

Califf, S., Early, D., Grotenhuis, M., Loto'aniu, T. M., & Kronenwetter, J. (2020). Correcting the arcjet thruster disturbance in GOES-16 magnetometer data. Space Weather, 18, doi:10.1029/2019SW002347.

Califf, S., Loto'aniu, T. M., Early D., and Grotenhuis, M. (2019), Arcjet Thruster Influence on Local Magnetic Field Measurements from a Geostationary Satellite, Journal of Spacecraft and Rockets, Vol. 57, No. 1, doi:10.2514/1.A34546

Carter, D., Early, D., Kronenwetter, J., Grotenhuis, M., Schnurr, R., and Todirita, M., (2019) GOES-16 Magnetometers Anomaly Solar-Angle Based Characterization & Correction, 2019 Annual Meeting of the American Meteorological Society.

Korotova, G., Sibeck, D., Thaller, S., Wygant, J., Spence, H., Kletzing, C., Angelopoulos, V.; Redmon, R. (2018) Multisatellite observations of the magnetosphere response to changes in the solar wind and interplanetary magnetic field, Annales Geophysicae, v 36, n 5, 1319-33, ISSN: 0992-7689; DOI: 10.5194/angeo-36-1319-2018

Loto'aniu, T. M., Redmon R., Califf, S., Singer, H.J., Rowland, W., Macintyre, S., Chastain, C., Dence, R., Bailey, R., Shoemaker, E., Rich, F.J., Chu, D., Early, D., J. Kronenwetter J. and Todirita, M. (2019) The GOES-16 Spacecraft Science Magnetometer, Advances in Space Research, 215: 32. https://doi.org/10.1007/s11214-019-0600-3.

Loto'aniu, T. M., Califf, S., Redmon, R. J., & Singer, H. J. (2020). Chapter 21 - magnetic field observations from the GOES-R series. In S. J. Goodman, T. J. Schmit, J. Daniels, & R. J. Redmon (Eds.), The goes-r series (p. 251- 412 259). Elsevier. doi: *https://doi.org/10.1016/B978-0-12-814327-8.00021-4*.

Miller, S. C. (2008), A magnetometer compensation scheme for countering thermally induced field Disturbances on the GOES-13 spacecraft, AIAA Guidance, Navigation and Control Conference and Exhibit, 2008, ISBN-13: 9781563479458.

Schnurr, R, T. Bonalsky, T., Todirita ,M., Kronenwetter, J., Early, D., Grotenhuis, M., Studer, R., Carter, D., Dence, R., Wolf, M., Mandi, J. (2019), Lessons Learned from Flight Observations of the GOES-R Magnetometer, 2019 ESA Workshop on Aerospace EMC (Aerospace EMC). Proceedings, p 6 pp.

Singer, H. J., Matheson, L., Grubb, R., Newman, A., Bouwer, S. D. (1996) Monitoring space weather with the GOES magnetometers, in GOES-8 and Beyond, Proc. SPIE, vol. 2812, edited by E. R. Washwell, pp. 299-308, Int. Soc. for Opt. Eng., Bellingham, Wash., doi: 10.1117/12.254077

Tsyganenko, N. A. (1989) A magnetospheric magnetic field model with a warped tail current sheet, Planet. Space Sci, 37, 5 -20, doi: 10.1016/0032-0633(89)90066-4.

Tsyganenko, N. A., Singer, H. J., Kasper, J. C. (2003) Storm-time distortion of the inner magnetosphere: How severe can it get? J. Geophys. Res., 108 (A5), 1209, doi:10.1029/2002JA009808.

Tsyganenko, N. A., Sitnov, M. I. (2005), Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, J. Geophys. Res., 110, A03208, doi:10.1029/2004JA010798

Woodger, L. A., Millan, R. M., Li, Z., Sample, J. G. (2018). Impact of background magnetic field for EMIC wave-driven electron precipitation. J. Geophys. Res., 123, 8518–8532. https://doi.org/10.1029/2018JA025315