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Long-Term Bias Stability of the GOES-NOP Magnetometers

S. Califf[1,2], F. J. Rich[3], T. M. Loto'aniu[1,2], H. J. Singer[4], and R. J. Redmon[2]

[1]Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA, [2]NOAA National Centers for Environmental Information, Boulder, CO, USA, [3]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, USA, [4]NOAA Space Weather Prediction Center, Boulder, CO, USA

Key Points:

- The GOES-NOP magnetometer biases are stable to within ~1–2 nT per axis from 2013 to 2018 on min, daily, seasonal and annual timescales
- Measurements mapped between spacecraft with TS04 can be used to separate error contributions from inboard and outboard magnetometers
- This is the first study to report the performance of the GOES-NOP magnetometers

Correspondence to:
S. Califf,
califf@colorado.edu

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Author Contributions:
Conceptualization: S. Califf
Methodology: F. J. Rich
Writing – original draft: S. Califf
Writing – review & editing: S. Califf, F. J. Rich, T. M. Loto'aniu, H. J. Singer, R. J. Redmon

Abstract We characterize the long-term bias stability of the GOES-NOP series magnetometers (GOES-13, 14, and 15) using data from 2013 through 2018. Bias stability is inferred using three methods: comparing the inboard and outboard measurements on each spacecraft, comparing the individual measurements to the TS04 magnetic field model, and comparing measurements between different GOES-NOP spacecraft. Comparisons between the inboard and outboard magnetometers demonstrate that GOES-14 and GOES-15 measurements are stable within approximately 1–2 nT. The GOES-13 inboard magnetometer has known contamination issues that hinder a useful inboard/outboard comparison, but inter-spacecraft comparisons with GOES-14 and GOES-15 indicate that the GOES-13 outboard magnetometer is also stable to 1–2 nT. Direct comparisons of each measurement to the TS04 magnetic field model support the conclusion that there is little long-term bias drift over the 6-year period. Model uncertainty and the variability of the field at geostationary orbit create a noise floor that is similar to the variability of the magnetometer biases. While these relative comparisons do not provide absolute measurement uncertainty, they do constrain the stability of the observations, allowing for future absolute calibration of the DC bias through different methods.

1. Introduction

The magnetometers on the Geostationary Operational Environmental Satellites (GOES) provide operational measurements of the magnetic field in geostationary orbit for space weather forecasts and alerts by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). GOES data have also been used extensively in scientific research for over 40 years, advancing our understanding of the coupled response of the Earth system to solar activity. The measurements offer context for the impact of geomagnetic storms on the Earth's magnetosphere, such as detecting the sudden storm commencement (SSC) that often occurs at the onset of a geomagnetic storm (e.g., Kokubun, 1983), geostationary magnetopause crossings (e.g., Singer et al., 1996), and geomagnetic substorms (e.g., Nagai, 1987). The magnetometers are also used to provide pitch angle information for the particle measurements onboard GOES (GOES 13-15 MAGE/PD PITCH ANGLES ATBD, 2014; Rodriguez et al., 2020), and the data have been a critical asset for developing magnetospheric magnetic field models (e.g., Tsyganenko & Sitnov, 2005, 2007; Sitnov et al., 2008). Additionally, the GOES magnetometer data have been used extensively to study waves in Earth's magnetosphere over a broad range of frequencies, including ion cyclotron waves (see e.g., Fraser et al., 2010) and lower frequency waves (see e.g., Takahashi et al., 2011).

GOES-13, -14, and -15 are the GOES-NOP satellites, and they were launched between 2006 and 2013. GOES-13 was operational as GOES-East at 75.2 deg W geographic longitude from 2010 to 2017 and was moved to a storage location at 60 deg W geographic longitude in 2018. GOES-13 was later transferred to the U.S. Air Force. GOES-15 was the operational GOES-West spacecraft at 137.2 deg W longitude from 2010 to 2018, and GOES-14 was held in the storage location at 105 deg W longitude.

GOES-16 and 17 from the new GOES-R series replaced GOES-13 and 15 in the GOES-East and GOES-West operational locations in 2018 and 2019, respectively. GOES-18 replaced GOES-17 in operations in 2023, and GOES-17 is now in a storage location with instruments turned off. During the initial on-orbit checkout phase for GOES-16, magnetic contamination issues were discovered, motivating design changes for GOES-17 (Loto'aniu et al., 2019). The magnetometers have been completely replaced for the GOES-18 and 19 spacecraft. Comparisons to GOES-NOP were used to diagnose problems in the new magnetometers, and GOES-14 was moved close to GOES-16 to directly compare the measurements. The GOES-NOP measurement accuracy has not been previously reported. This study establishes the performance of the GOES-NOP magnetometers.

Evaluating the accuracy of geostationary magnetometers on three-axis stabilized spacecraft is challenging because there is no truth measurement available for reference. Magnetic field models at geostationary orbit are limited by incomplete physics, inadequate spatial and temporal observations, and the use of imperfect measurements to develop the models. Inter-spacecraft comparisons suffer from uncertainties in the reference spacecraft measurement and mapping between the two spacecraft over large distances. Error estimates derived from comparisons between measurements and models or between measurements from two spacecraft only describe the relative error, but these comparisons are useful for establishing the stability of the magnetometers.

The GOES magnetometer accuracy requirement is 1 nT (per axis), and there is an additional requirement that the uncompensated bias sensitivity to temperature must be less than 4 nT (GOES N Data Book, 2006). For comparison, the magnetometer onboard the South Korean meteorological and environmental satellite GEO-KOMPSAT-2A has a 5 nT accuracy requirement for signals below 0.1 mHz (Magnes, et al., 2020). The GEO-KOMPSAT-2A magnetometer accuracy was verified through comparisons to GOES-14 and GOES-15 data, and the biases were defined relative to the TS04 magnetic field model (Tsyganenko & Sitnov, 2005). The initial on-orbit bias was found to be 90 nT in one axis, which highlights the importance of on-orbit calibration and validation, as biases determined through ground calibration can change after launch. The Magnetospheric MultiScale (MMS) mission achieved an accuracy of ∼0.1 nT due to advantages provided by the spin-stabilization, allowing continuous calibration of the spin-plane measurement (Plaschke, et al., 2019). The Swarm satellites are equipped with an absolute scalar magnetometer and a fluxgate magnetometer, resulting in measurement accuracy of approximately 1 nT (Friis-Christensen et al., 2006).

To achieve the NOAA accuracy requirements, the bias, which is a static offset between the measurement and truth, has to be determined, and the bias also has to be stable over the lifetime of the mission. The GOES magnetometers are calibrated through a series of spacecraft rotations during the on-orbit checkout phase of each mission, providing point estimates for the absolute calibration assuming that the instrument scale factors are known. The calibration maneuver bias estimate has uncertainties of several nanoteslas due to physical variations in the geomagnetic field and the geometry of the spacecraft rotations, and on-orbit calibration does not address calibration variations on daily, seasonal, or annual timescales. We focus on the stability of the measurements, which can be established by comparing data from inboard (IB) and outboard (OB) magnetometers on each spacecraft. Individual error signals from the inboard and outboard magnetometers are then examined through relative comparisons to other GOES spacecraft and the TS04 magnetic field model.

The purpose of this study is to establish the stability of the GOES-NOP magnetometer biases on minute, daily, seasonal and annual timescales, which has not been previously reported. The data have been used for a wide range of operational and scientific applications, and each application and user have unique goals with different timescales of interest and different tolerances for measurement error. For example, detecting magnetopause crossings at geosynchronous orbit may be insensitive to ∼10 nT errors, as the measured magnetic field changes on the order of 100 nT when the magnetopause moves across the spacecraft. On the other hand, diurnal bias variations at geostationary orbit map to systematic local time errors, so a systematic 10 nT diurnal bias error could introduce a relatively large spatial error if the data were used in an empirical magnetic field model. Bias variations could also affect the interpretation of energetic particle measurements on GOES-NOP as the magnetic field measurements are used to compute particle pitch angles. Additionally, the GOES-NOP magnetometers were used for on-orbit validation for GOES-16 and GOES-17 (GOES-16 PS-PVR, 2017; GOES-17 PS-PVR, 2021), and this comparison relies on the assumption that the GOES-NOP biases are stable. Here we report the bias stability as a reference for data users.

The GOES NOP magnetometers and data are described in Section 2. Section 3 evaluates the relative errors between the inboard and outboard magnetometers on each spacecraft. GOES NOP measurements are compared to the TS04 model in Section 4, and inter-spacecraft comparisons are examined in Section 5. Section 6 provides conclusions of the study.

2. GOES-NOP Magnetometers and Data

Each GOES-NOP spacecraft has two triaxial fluxgate magnetometers built by Science Applications International Corporation (SAIC), that are mounted on an 8.5 m boom. The inboard magnetometer is located 7.7 m from the spacecraft, and the outboard magnetometer is mounted at the end of the boom, such that approximately

0.8 m separates the inboard from the outboard—the magnetometers are very close together and ideally measure the same ambient magnetic field. The data are sampled at 1.95 samples/second, and the 16-bit A/D converter with ±512 nT range results in 0.03 nT resolution (Tables 5–9, GOES N Data Book, 2006). Raw counts from the A/D converter are transmitted to the ground, where they are converted to physical units and rotated into the Earth-Poleward-Normal coordinate system (e.g., Loto'aniu et al., 2019). No temperature compensation is applied to GOES-NOP magnetometer data.

Operational data were transmitted to SWPC and processed in real time, and the data were archived by the National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/data/goes-space-environment-monitor/access/science/mag/goes14). One-minute averages are provided in addition to the original full-resolution data. GOES-14 storage mode data were initially transmitted to the NOAA Spacecraft Operational Facility (NSOF). These data were later recovered and processed using a modified version of the SWPC processing algorithm, and they are now publicly available as part of this work on the NCEI website (https://www.ncei.noaa.gov/data/goes-space-environment-monitor/access/science/mag/goes14_storage_mode_mag). This study uses 1-min averages to evaluate the stability of the magnetometers.

3. Inboard-Outboard Comparisons

The purpose of the two magnetometers on GOES-NOP was for redundancy in observations of the geomagnetic during NOAA operations. Having two magnetometers separated along a boom can also allow the removal of time-varying spacecraft magnetic fields by applying the gradiometric technique, where measurements at different locations are used to estimate a magnetic dipole originating at the spacecraft (Ness et al., 1971). The absolute bias uncertainty and bias variations on GOES-NOP were too large to produce useful estimates of the spacecraft field, particularly for inboard magnetometer on GOES-13. For this study, the differences between the inboard and outboard magnetometers are assumed to primarily reflect measurement errors in one or both magnetometers.

3.1. Diurnal Variation

Figure 1 shows the difference between the inboard and outboard magnetometers on GOES-13 between 2015-06-01 and 2015-07-01 as a function of solar local time (LT). One-minute averages are plotted for the entire month in blue, and differences for 2015-06-01 are plotted in green to show an example of a particular day of relative bias variations. There are large diurnal variations in each component of the measurement that repeat consistently over the entire month. These errors are thought to be related to thermoelectric currents near the inboard magnetometer, which led to the outboard magnetometer being used exclusively for operations. GOES are nadir pointing spacecraft in geostationary orbit, so the orientation of the sun relative to the spacecraft repeats daily and also has a seasonal modulation. The diurnal variations between inboard and outboard magnetometers on the same GOES spacecraft are likely caused by thermal variations—fluxgate magnetometers and A/D converters are sensitive to temperature and thermal gradients, and thermal variations can cause magnetic contamination by affecting nearby magnetic material or generating thermoelectric currents (Schnurr et al., 2019). Magnetic cleanliness and thermal considerations are critical to producing a clean magnetometer measurement in space (Acuna, 2002).

The relative diurnal variation between the inboard and outboard magnetometers for GOES-14 is displayed in Figure 2. Note that the y-axis ranges are much smaller in Figure 2 than Figure 1. The relative static biases are approximately 3 nT in the E component, 1 nT in the P component and <1 nT in the N component, which reflect uncertainties in the biases derived from the calibration maneuver for one or both of the magnetometers. We are interested in the bias stability, which is approximately ±1 nT or better over the course of a day in all axes. The diurnal patterns are also stable over the entire month, with the exception of the excursion in the N component near local midnight, which occurred on a single day when there was strong geomagnetic activity (Kp = 6). Differences between the inboard and outboard magnetometers related to variations in the ambient field during geomagnetic storms are caused by relative scale factor or alignment errors between the two magnetometers, so these errors are small and don't have a significant impact on the long-term trends between the inboard and outboard magnetometers. In this case, the increased N component differences between the inboard and outboard magnetometers on that day were correlated with a strong increase in the E component magnitude, which suggests that there are small relative alignment errors between the two magnetometers.

There is a systematic pattern with local time in the E component difference, suggesting a thermal dependence in one or both of the magnetometers. In the P and N components, the systematic diurnal variation is small, and

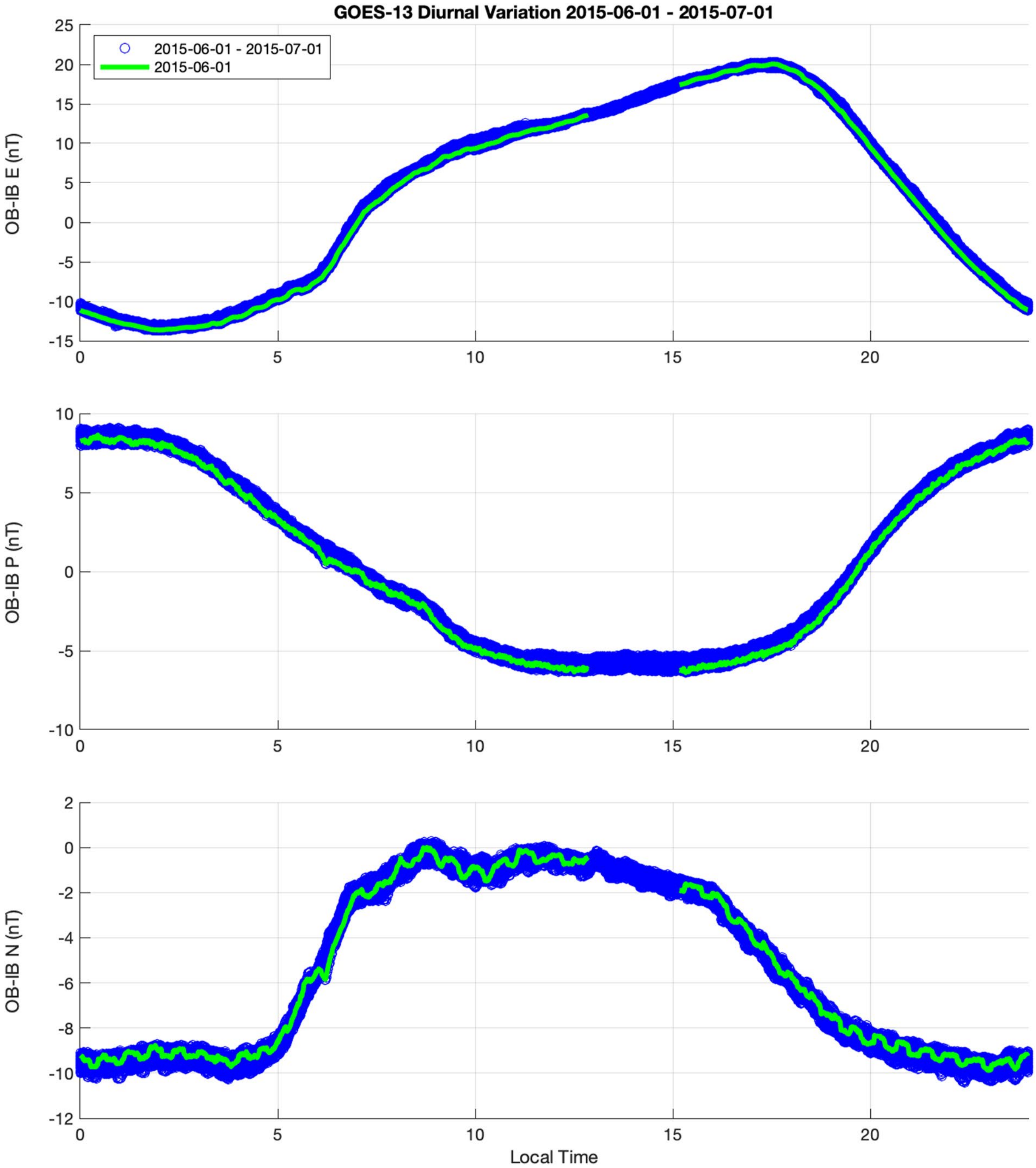

Figure 1. Difference between GOES-13 outboard and inboard magnetometer measurements during June 2015.

periodic steps are present in the data that were attributed to interference from the sensor heaters. In addition to the diurnal patterns, there are static offsets between the inboard and outboard measurements. The magnetometer biases were estimated early in the mission by performing a series of spacecraft rotations, and these biases were applied in the ground processing software. The static offsets indicate that there were errors in the original bias estimates for one or both magnetometers.

GOES-15 displays similar diurnal stability to GOES-14 (Figure 3). There is a systematic E component signal, but it is smaller than the GOES-14 E component diurnal variation. The periodic steps related to heater are also present in the GOES-15 data. The spacecraft is nadir pointing, and the magnetometers are mounted on a boom that

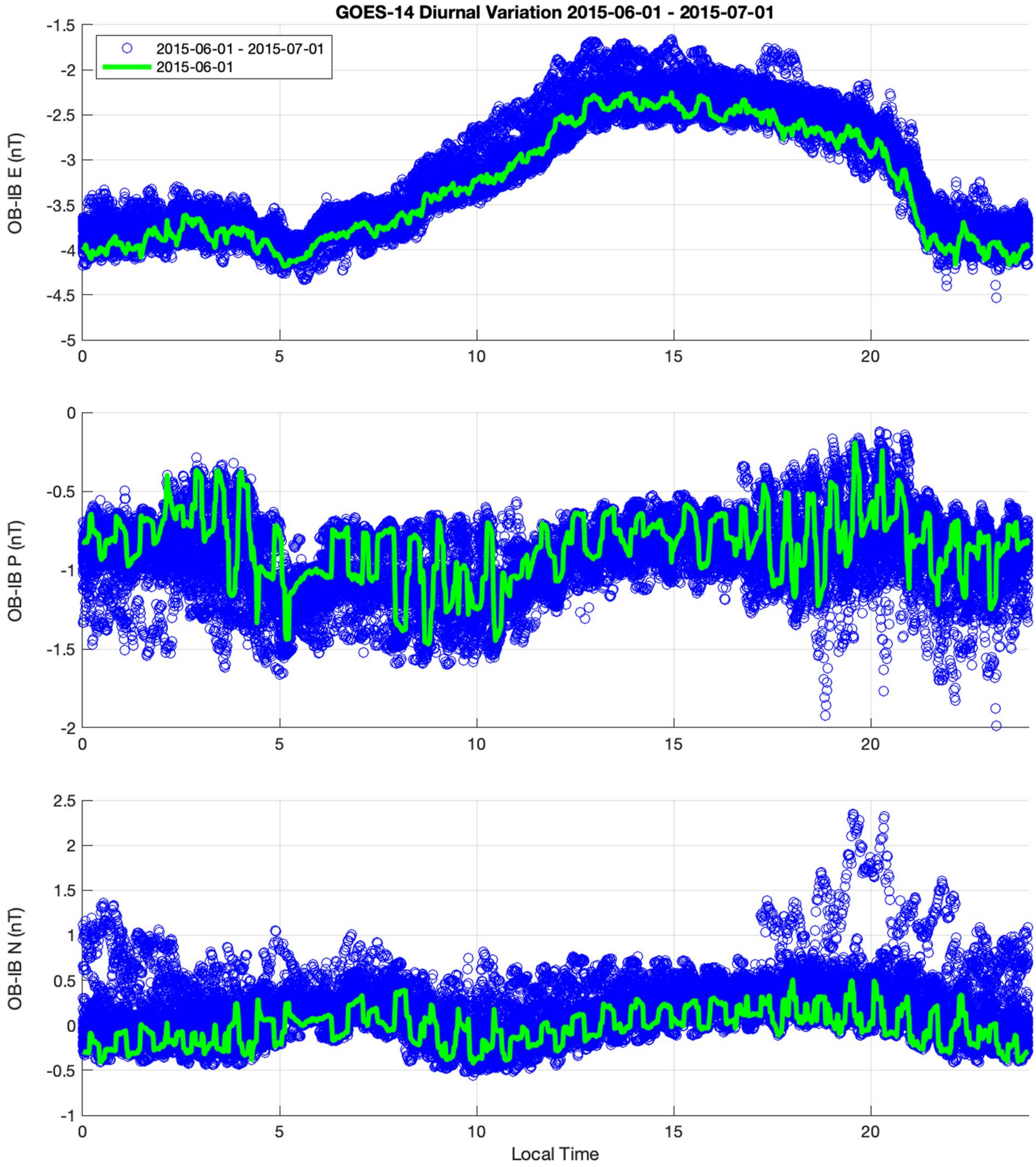

Figure 2. Difference between GOES-14 outboard and inboard magnetometer measurements during June 2015.

points away from nadir and is canted to one side. This causes the magnetometers to be most directly illuminated by the sun between 5 and 9 LT, so the heaters are inactive in those local times.

3.2. Long-Term Bias Stability

The inboard and outboard measurements from GOES-14 from 2013 to 01-01 to 2018-12-31 (6 years) are compared in Figure 4. The daily means of one-minute averages are plotted in green, the blue lines represent one standard deviation about the mean, and the daily minimum and maximum differences are shown in black. A

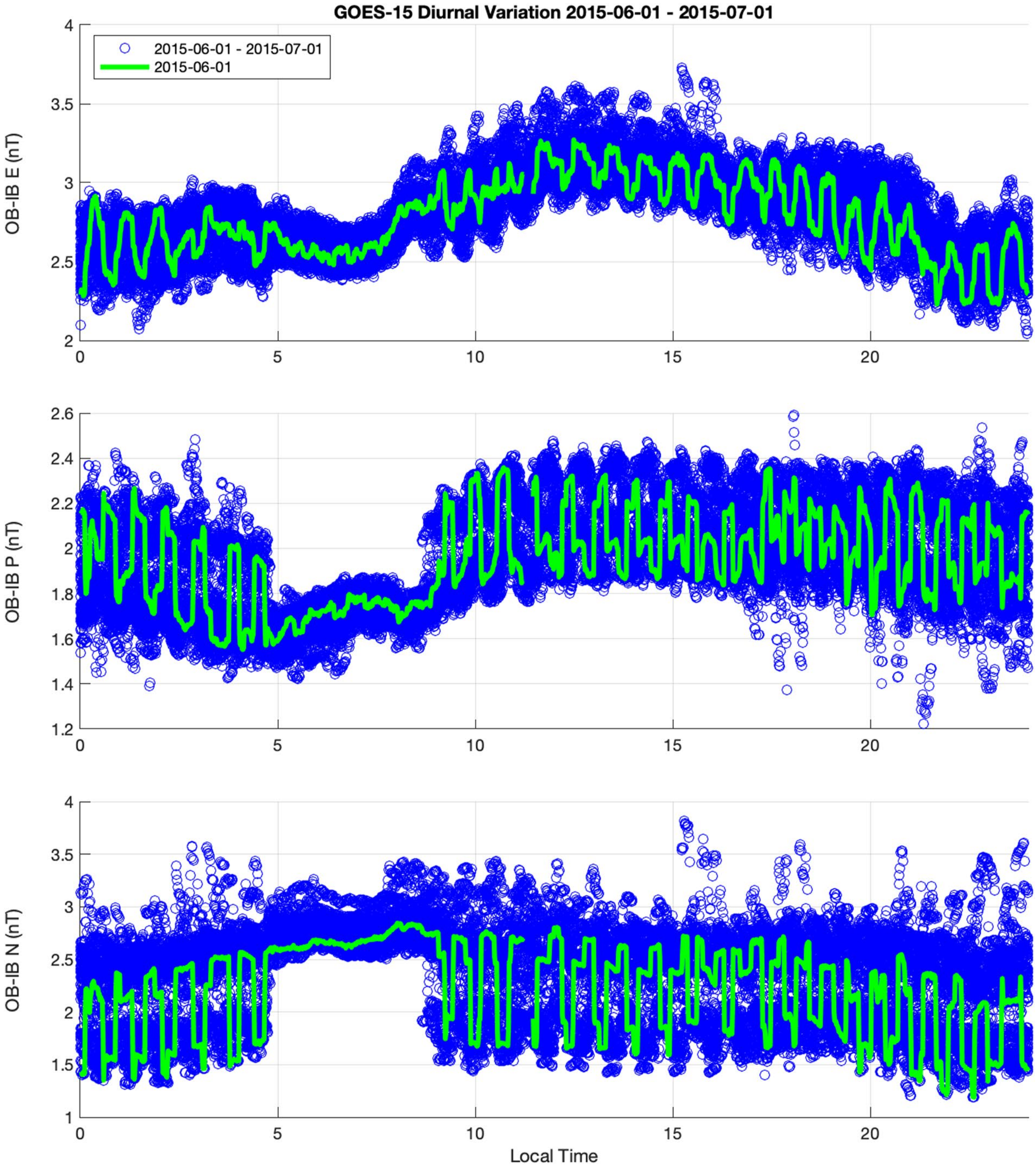

Figure 3. Difference between GOES-15 outboard and inboard magnetometer measurements during June 2015.

small number of days (<3%) were removed from the data set due to data gaps and anomalous spikes in the data. A period of generally higher variability between 2013-02-13 and 2013-05-24 related to operational configuration tests has also been excluded. The increased variability in the P component during 2015 is also likely a result of configuration tests.

The relative daily averages are stable—the daily mean differences between the inboard and outboard magnetometers on GOES-14 agree to within approximately 1 nT over the 6-year period, excluding anomalies and data outage periods. There are seasonal variations in the E and N components, suggesting a thermal dependence to the biases as the sun angle changes throughout the year. In the E component, the daily standard deviation (blue lines)

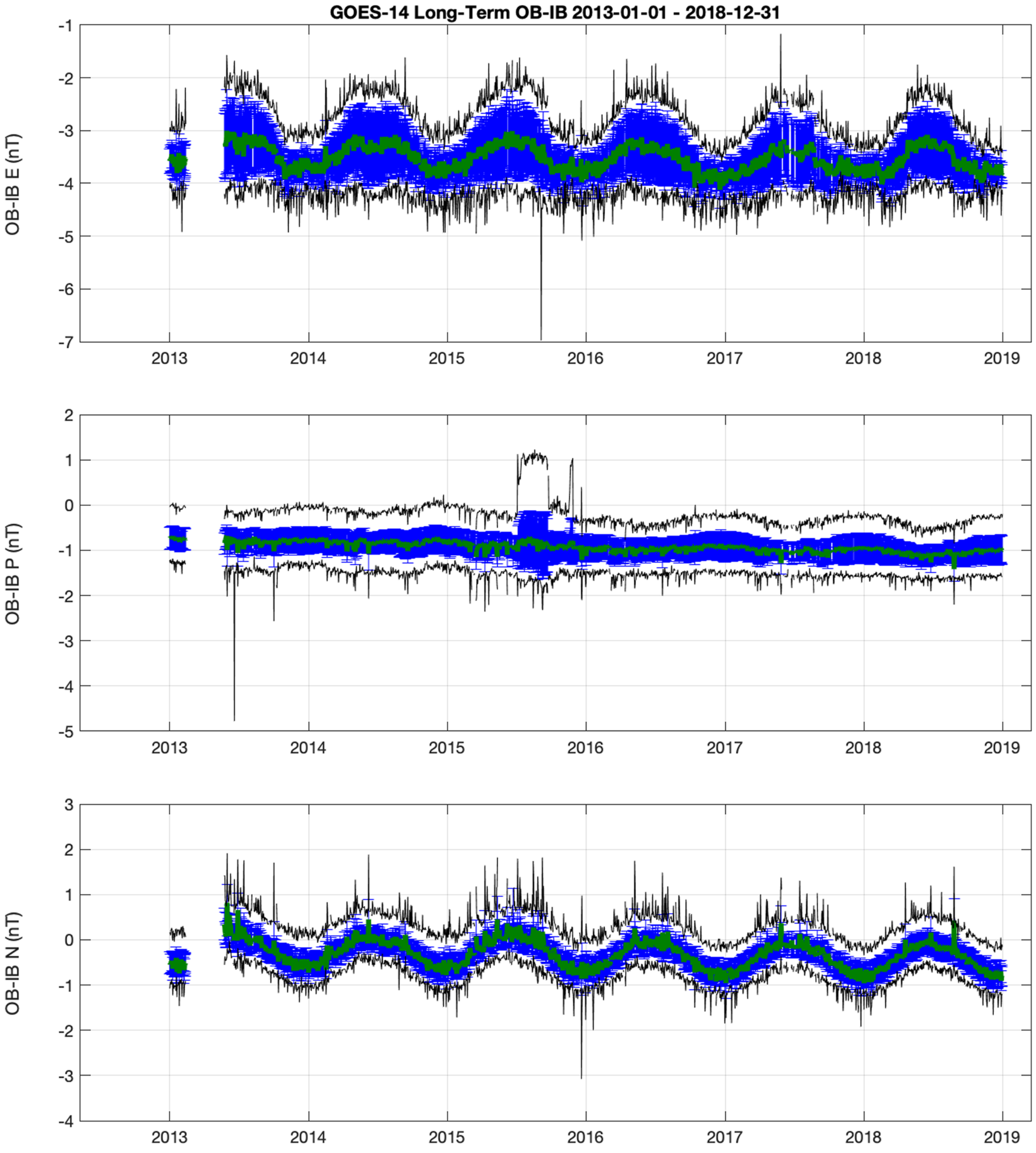

Figure 4. Differences between GOES-14 inboard and outboard magnetometers from 2013 to 2018. Daily means of the differences are plotted in green, one-sigma daily error bars are plotted in blue, and the daily minimum and maximum are plotted in black.

and daily minimum and maximum (black lines) also vary seasonally, with larger diurnal variations between the two magnetometers occurring in the northern-hemisphere summer months. A linear fit to the data produces a bias drift of less than 0.1 nT/year in all components.

Figure 5 shows the long-term comparison between the inboard and outboard magnetometers for GOES-15 in the same format as Figure 4. Approximately 4% of the days were excluded from the data set due to anomalous spikes in the data. The step changes are caused by biannual yaw flips, where the spacecraft is rotated by 180 deg about the nadir-pointing axis for thermal control purposes. Since the spacecraft rotates about nadir (E direction), biases in the spacecraft frame switch sign in the P and N components. If the biases were the same before and after each

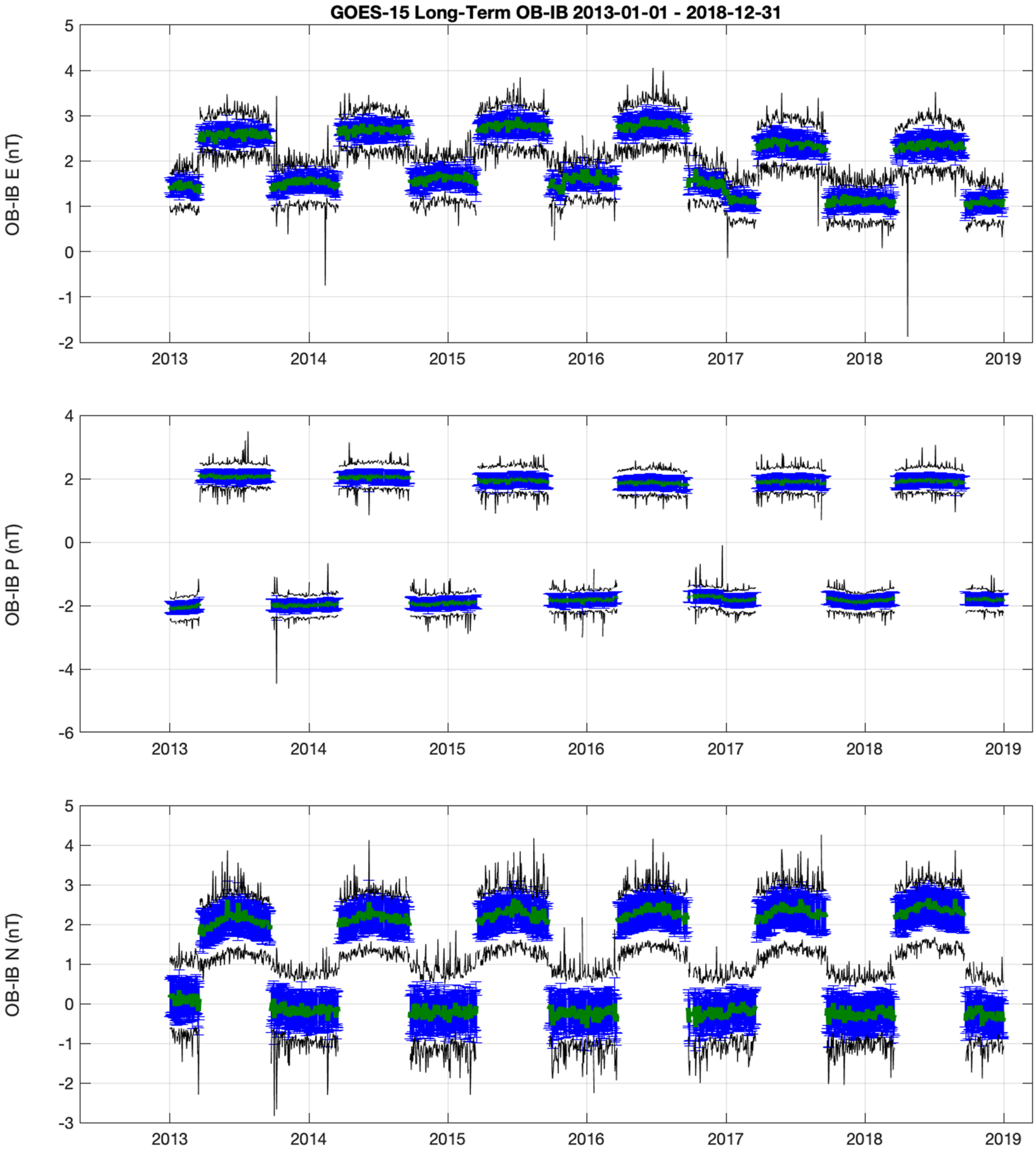

Figure 5. Differences between GOES-15 inboard and outboard magnetometers from 2013 to 2018. Daily means of the differences are plotted in green, one-sigma daily error bars are plotted in blue, and the daily minimum and maximum are plotted in black.

yaw flip, the inboard-outboard difference would be constant in the E component, and the P and N component differences would change sign symmetrically about zero. The offsets in the E and N components indicate that the E and N biases change during the yaw flip, so separate bias terms should be applied depending on whether the spacecraft is upright or flipped. However, the biases are stable within 0.5 nT in a given yaw flip configuration.

The steps in Figure 5 show that there are changes in the relative biases during yaw flips, but the relative measurements do not provide information on whether the changes occur in the inboard magnetometer, the outboard magnetometer, or both. To investigate the source of the relative bias shifts, we estimated the GOES-15 bias corrections independently for the inboard and outboard magnetometers in each yaw flip state using the GOES-14

Table 1
GOES-15 Bias Correction for Upright and Inverted Yaw Flip States Relative to GOES-14 Outboard Measurements

	OB E (nT)	OB P (nT)	OB N (nT)	IB E (nT)	IB P (nT)	IB N (nT)
Inverted (March-Sept)	3.31	−0.21	1.23	0.73	−2.16	−1.02
Upright (Sept-March)	6.14	0.03	0.7	4.76	1.91	0.91

outboard magnetometer as a reference. The TS04 model was subtracted from each measurement to account for the 2-hr local time separation between the spacecraft, and the biases were computed using the mean of the one-minute averaged differences in each yaw flip state between 2013 and 2018.

The GOES-15 biases relative to GOES-14 are presented in Table 1, and the yaw flip dates are provided in Table 2. In the E component, both GOES-15 inboard and outboard biases shift in the same direction by 3–4 nT after yaw flips, but only the relative change is captured by the inboard-outboard comparison in Figure 5. The cause of the bias shift during yaw flips is unknown, but it could be related to changes in the spacecraft field between upright and flipped yaw orientations, or changes in the thermal environment near the magnetometers. For the P and N components, the comparison to GOES-14 suggests that most of the bias shift occurs in the GOES-15 inboard magnetometer, while the GOES-15 outboard magnetometer P and N bias estimates are consistent to within ~0.5 nT before and after yaw flips. The inboard magnetometer P and N biases switch signs, which suggests an absolute calibration error of ~2 nT in the P component and ~1 nT in the N component. Figure 6 shows the GOES-15 inboard-outboard comparison after applying the yaw flip bias correction. Small bias shifts remain in the data near yaw flips, but the corrected data are stable to better than ±1 nT over the 6-year interval.

While the absolute biases cannot be derived from relative comparisons between spacecraft, the variation in the relative biases in Table 1 indicates that the measurements have absolute uncertainties of several nanotelsas. The biases are estimated based on a calibration maneuver during the initial checkout phase of each mission. The calibration maneuver consists of a series of spacecraft rotations, and the biases in each axis can be derived assuming that the biases and the background field are constant during the maneuver. Although the calibration maneuver is performed at local noon under quiet geomagnetic conditions, geophysical fluctuations and systematic local time variations inevitably occur during the rotations, creating uncertainty in the bias estimates. Additionally, the bias shifts related to yaw flips for GOES-15 indicate that the biases change as the spacecraft is rotated, further increasing uncertainty the absolute biases.

4. Direct Comparison Between GOES-NOP and TS04

In this section we compare the outboard magnetometer measurements from each GOES-NOP spacecraft to the TS04 magnetic field model from 2013 to 2018. The TS04 model provides an empirical representation of Earth's magnetospheric magnetic field using 5-min solar wind measurements and geomagnetic indices as an input (Tsyganenko & Sitnov, 2005). The true field at geostationary orbit is highly variable and spatially structured, especially during geomagnetically active times, and differences between the model and the observations are expected. The purpose of this comparison is to examine the long-term stability GOES-NOP measurements relative to an independent model.

Figure 7 shows the long-term difference between GOES-13 outboard measurements and TS04. Daily means and one-sigma variations about the mean were computed using one-minute data. The daily standard deviations often exceed the ±15 nT limits of the plot, which primarily reflects the variable nature of geomagnetic field and unmodeled dynamics in the TS04 model. Despite the short-timescale variations between the model and the measurement, the DC bias appears to be stable over the 6-year period. This is more apparent in the N component (bottom panel), which interpreted as a consequence of the geomagnetic field being less variable in the azimuthal direction at geostationary orbit. The larger variations are related to compression and stretching in response to solar wind driving, which has a larger effect in the E

Table 2
GOES-15 Yaw Flip Dates

Upright to inverted	Inverted to upright
3/20/13	9/23/13
3/20/14	9/23/14
3/19/15	9/23/15
3/21/16	9/22/16
3/21/17	9/21/17
3/20/18	9/20/18

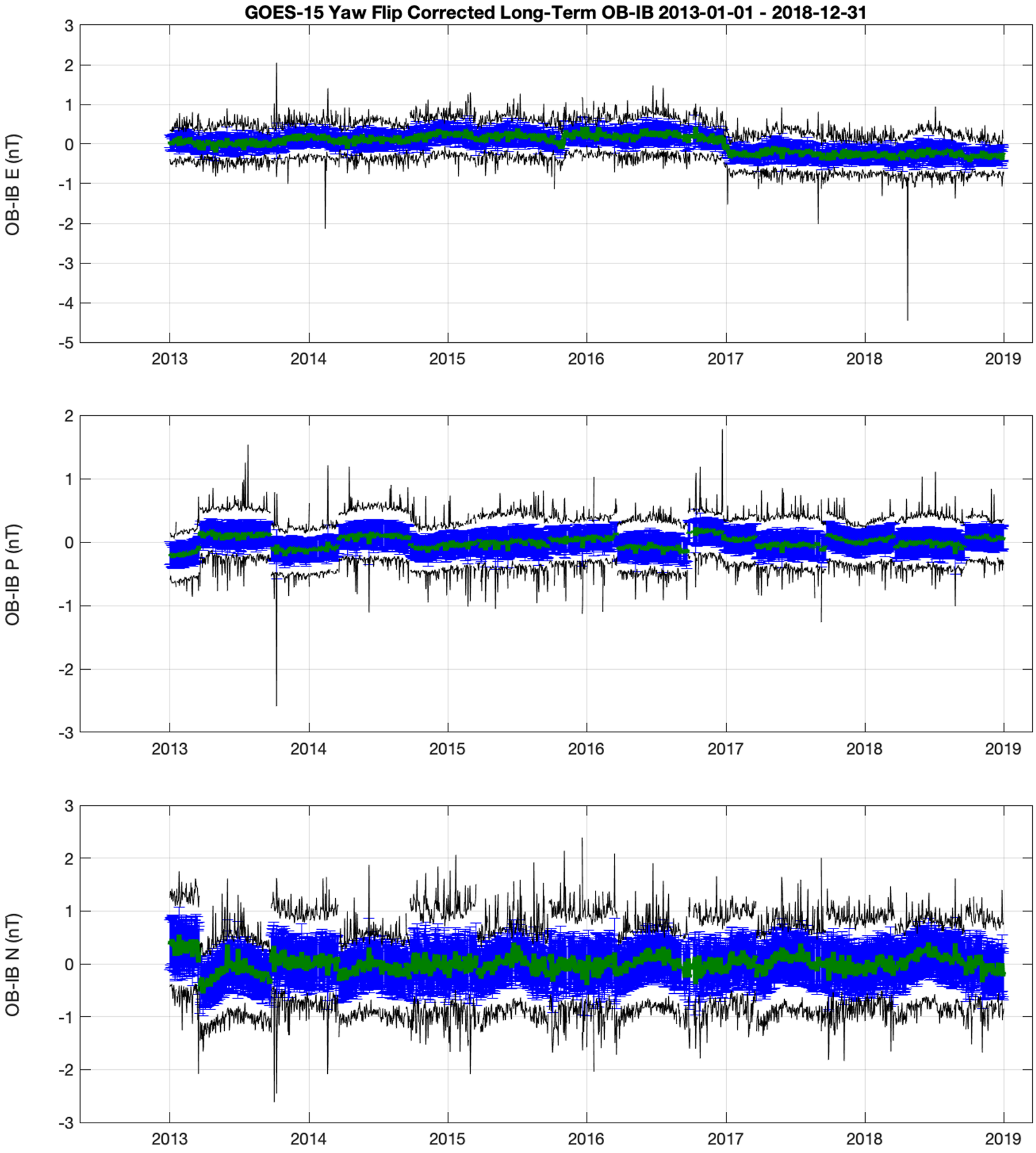

Figure 6. Differences between GOES-15 inboard and outboard magnetometers from 2013 to 2018 after correcting for bias shifts related to yaw flips. Daily means of the differences are plotted in green, one-sigma daily error bars are plotted in blue, and the daily minimum and maximum are plotted in black.

and P components. Our interpretation is that the long-term bias drift of the GOES-13 outboard magnetometer is smaller than the uncertainty in the TS04 model.

There is a sinusoidal seasonal variation in the GOES-13 E component comparison that is also present in the GOES-14 and GOES-15 comparisons in Figures 8 and 9. Given that the GOES-14 and GOES-15 inboard/outboard comparisons did not reveal similar seasonal variations, this signal likely originates from the TS04 model rather than the measurements. The E component measures the earthward deflection of the magnetic field, and the E component tends to be larger when the spacecraft is off the magnetic equator, especially on the night side. There is also a seasonal variation in the mean observed E component at GOES, which may be related to well-known

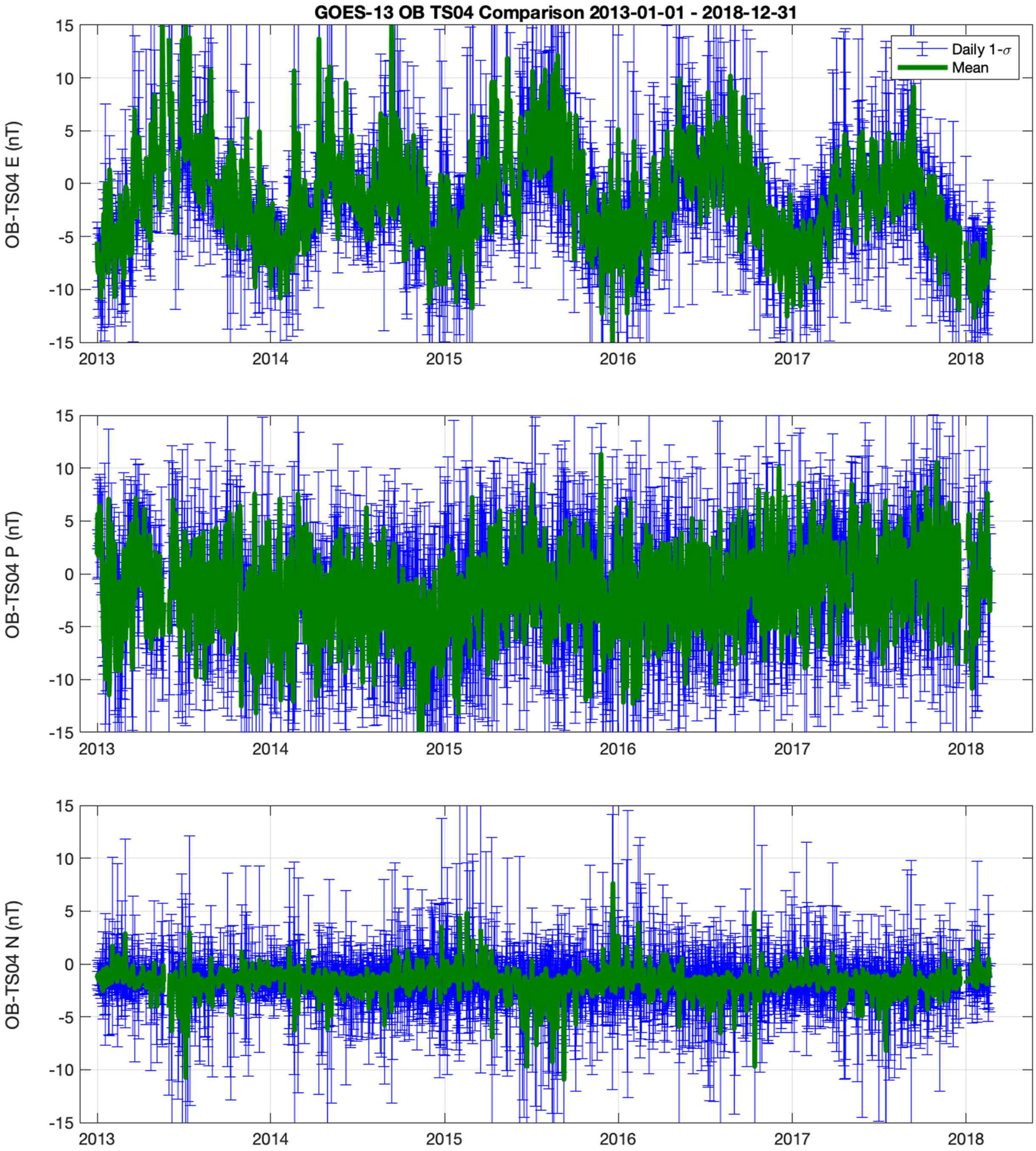

Figure 7. Long-term comparison between GOES-13 outboard magnetometer measurements and TS04. Daily means of the difference are plotted in green and one-sigma daily error bars are plotted in blue.

semiannual variation in geomagnetic activity caused by the angle between the sun and Earth's dipole (Russell & McPherron, 1973). This suggests that there may be systematic errors in the TS04 model at locations away from the magnetic equator. However, the seasonal variation does not affect the purpose of the comparison, which is to demonstrate that the biases of the instruments are stable over a 6-year period.

The GOES-14 and GOES-15 comparisons to TS04 show similar trends in Figures 8 and 9, with larger variations in the E and P components, and more stability in the N component, which we interpret as being primarily driven by model errors. Both GOES-14 and GOES-15 show potential evidence of small long-term bias drifts relative to the model in the P component, but these drifts are unlikely to be larger than a couple nanoteslas over six years.

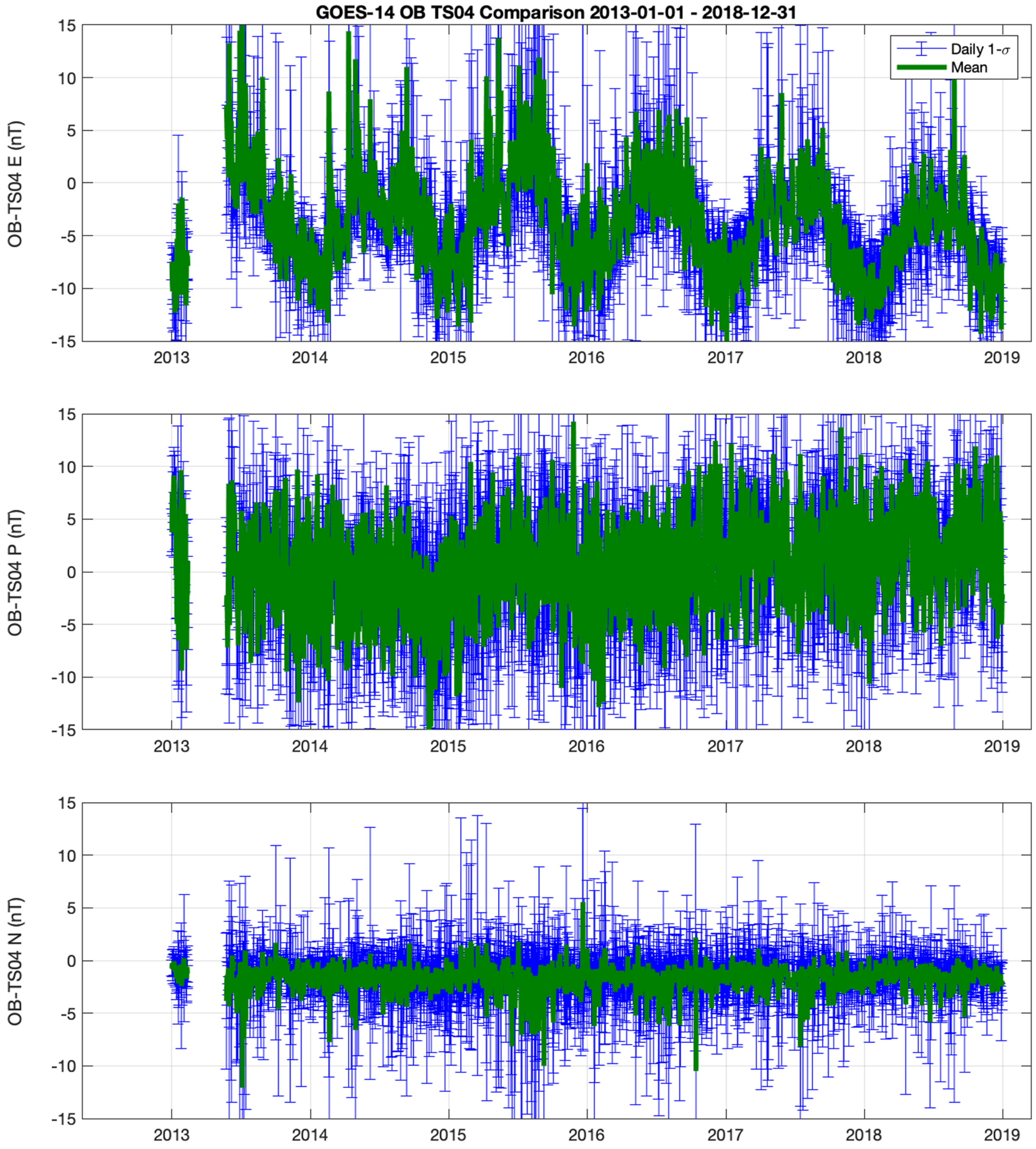

Figure 8. Long-term comparison between GOES-14 outboard magnetometer measurements and TS04. Daily means of the difference are plotted in green and one-sigma daily error bars are plotted in blue.

5. Inter-Spacecraft Comparisons

For GOES-14 and GOES-15, the inboard and outboard magnetometers are stable relative to each other within approximately ±1 nT on daily and annual timescales. This suggests that each magnetometer is stable to within ±1 nT, as it is unlikely that both magnetometers would have large correlated bias variations. For GOES-13, the relative diurnal variation between the inboard and outboard magnetometers is too large to draw similar conclusions. Therefore, we use inter-spacecraft comparisons relative to GOES-14 and GOES-15 to estimate the stability of the GOES-13 measurements.

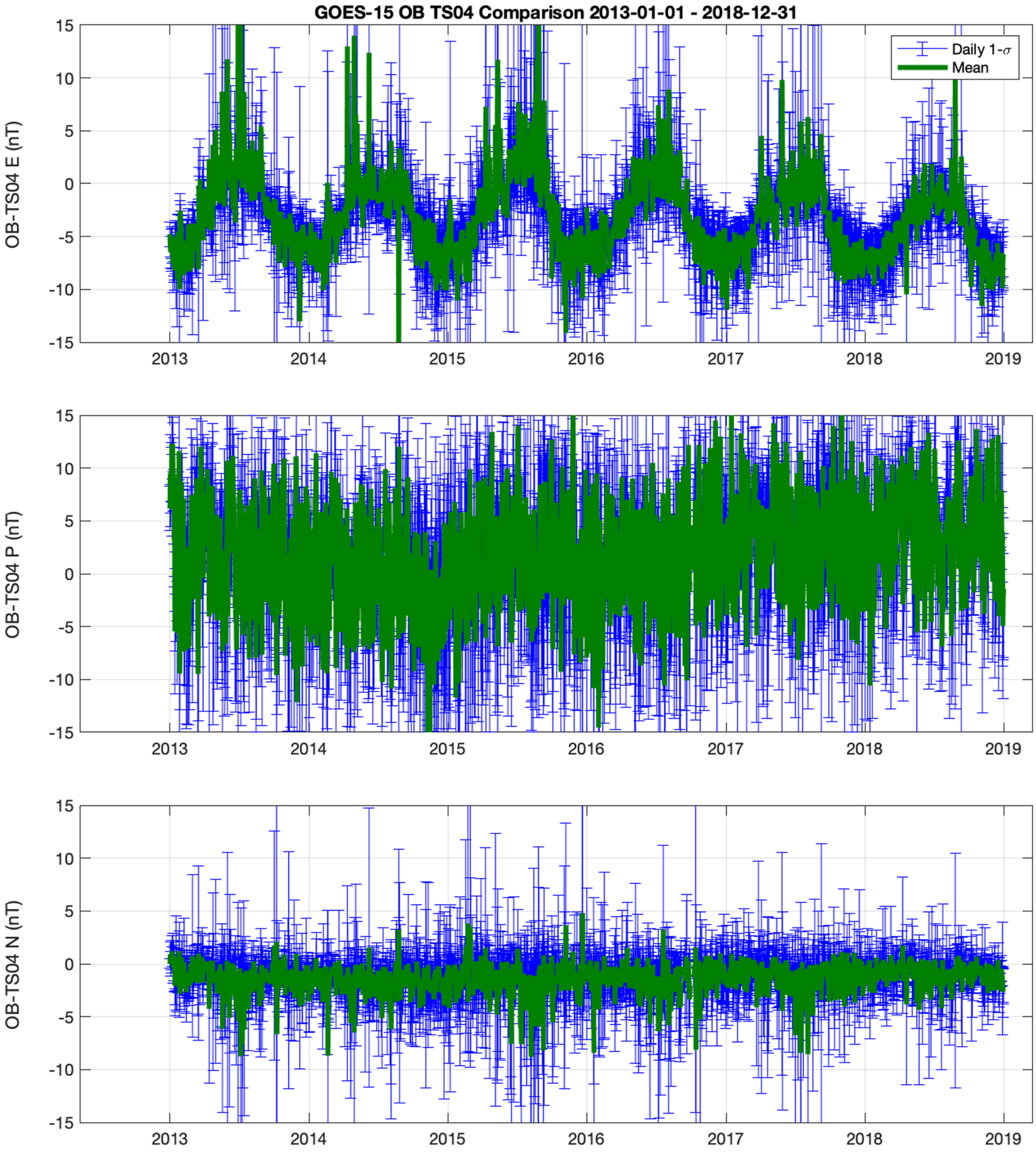

Figure 9. Long-term comparison between GOES-15 outboard magnetometer measurements and TS04. Daily means of the difference are plotted in green and one-sigma daily error bars are plotted in blue.

First, we compare the diurnal variation in GOES-14 and GOES-15 in Figure 10 to demonstrate the inter-spacecraft comparison approach. The TS04 model was subtracted from each of the one-minute averaged measurements to account for differences in spacecraft location, and the differences were averaged in one-hour local time bins from 2013 to 2018. Given that GOES-14 has larger systematic diurnal variations in the E component, the GOES-15 outboard magnetometer was selected as the reference magnetometer. The static yaw flip corrections from Section 3 were applied to the GOES-15 data, and the mean has been subtracted from each curve to focus on the local time dependence (diurnal variation). The local time in Figure 10 reflects the local time of GOES-14.

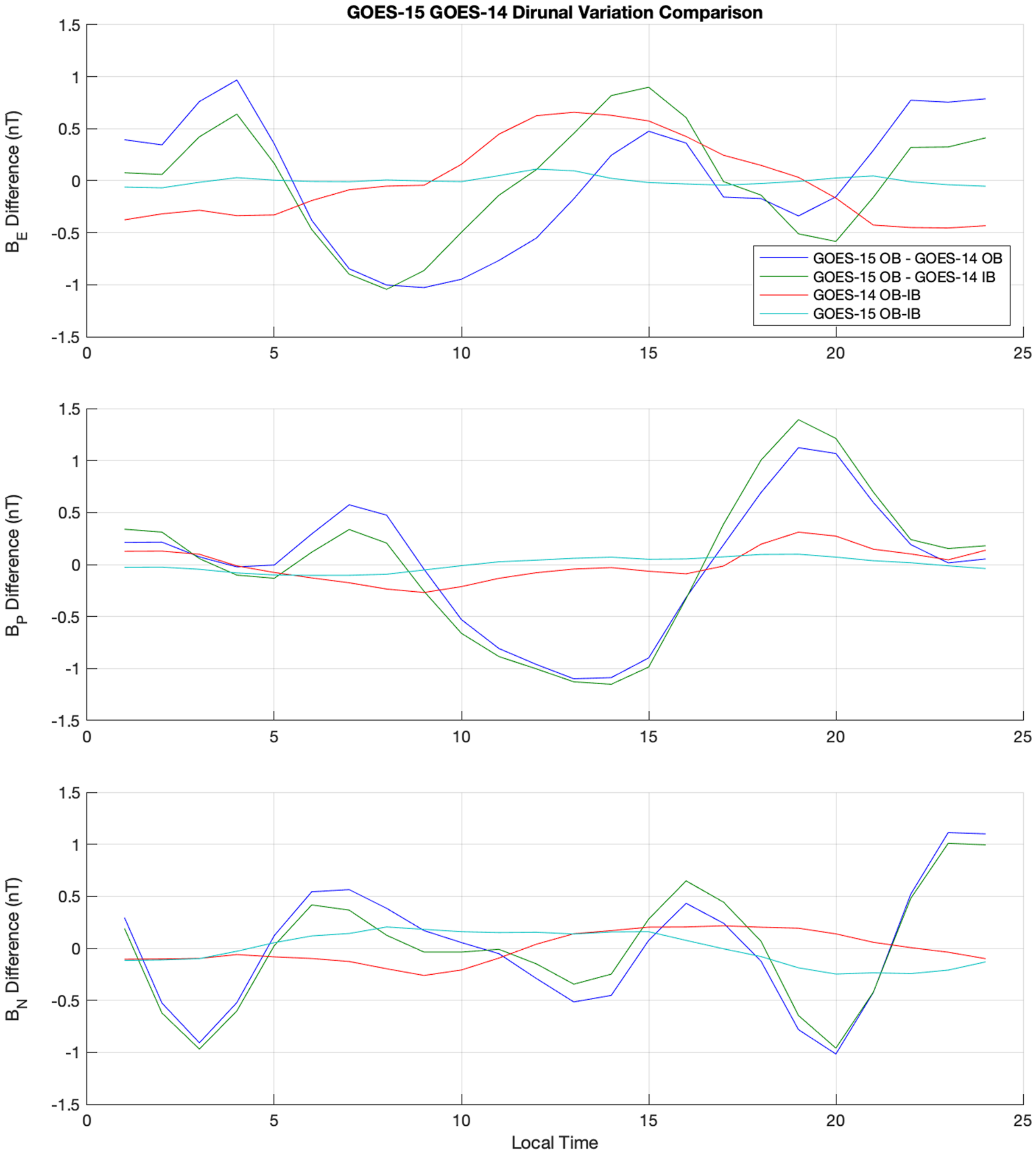

Figure 10. Comparison between GOES-14 and GOES-15 magnetometers as a function of solar local time between 2013 and 2018. The TS04 model has been subtracted from all measurements to account for longitudinal separation of the spacecraft. Inboard/outboard differences for each spacecraft are plotted in red and cyan.

The inter-spacecraft comparisons show larger systematic local time variations than the individual inboard-outboard differences on either spacecraft. We attribute this to systematic errors in the TS04 model that is used to map measurements between the spacecraft. Despite the mapping uncertainties, the GOES-15 outboard magnetometer agrees with both GOES-14 magnetometers to within ±1.5 nT in all components. The largest systematic diurnal variation detected in the inboard-outboard comparison is in the GOES-14 E component (Figure 10, red line), however, it is unclear from comparison to GOES-15 whether the error is due to the inboard or outboard magnetometer on GOES-14. However, this comparison does support the conclusion that there are no large correlated systematic diurnal errors between the inboard and outboard magnetometers on GOES-14.

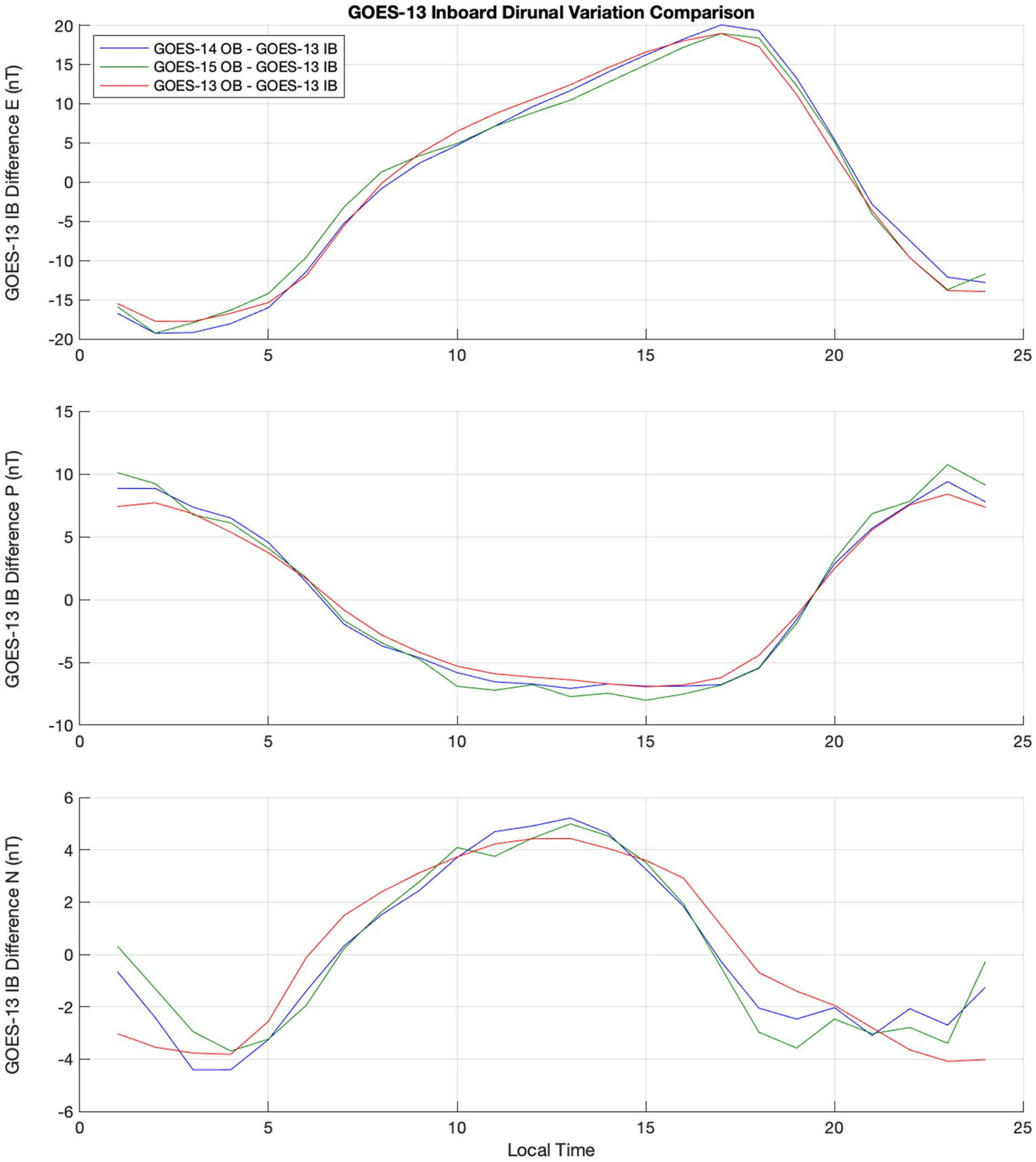

Figure 11. Comparison between GOES-13 inboard magnetometer measurements and GOES-14 and GOES-15 outboard measurements. The TS04 model has been subtracted from all measurements to account for longitudinal separation of the spacecraft.

In Figure 11, the GOES-13 inboard measurements are compared to outboard measurements from GOES-14 and GOES-15 using the same methodology as Figure 10. The local time in Figure 11 is determined by the location of GOES-13. The independent comparisons to GOES-14 and GOES-15 closely match the local time pattern of GOES-13 inboard-outboard differences (red line), confirming that the error observed on GOES-13 is mostly driven by the inboard magnetometer. This demonstrates that mapping geostationary magnetometer measurements at different longitudes using TS04 is a viable method to identify large systematic error signals, given that the stability of the reference measurement can be verified.

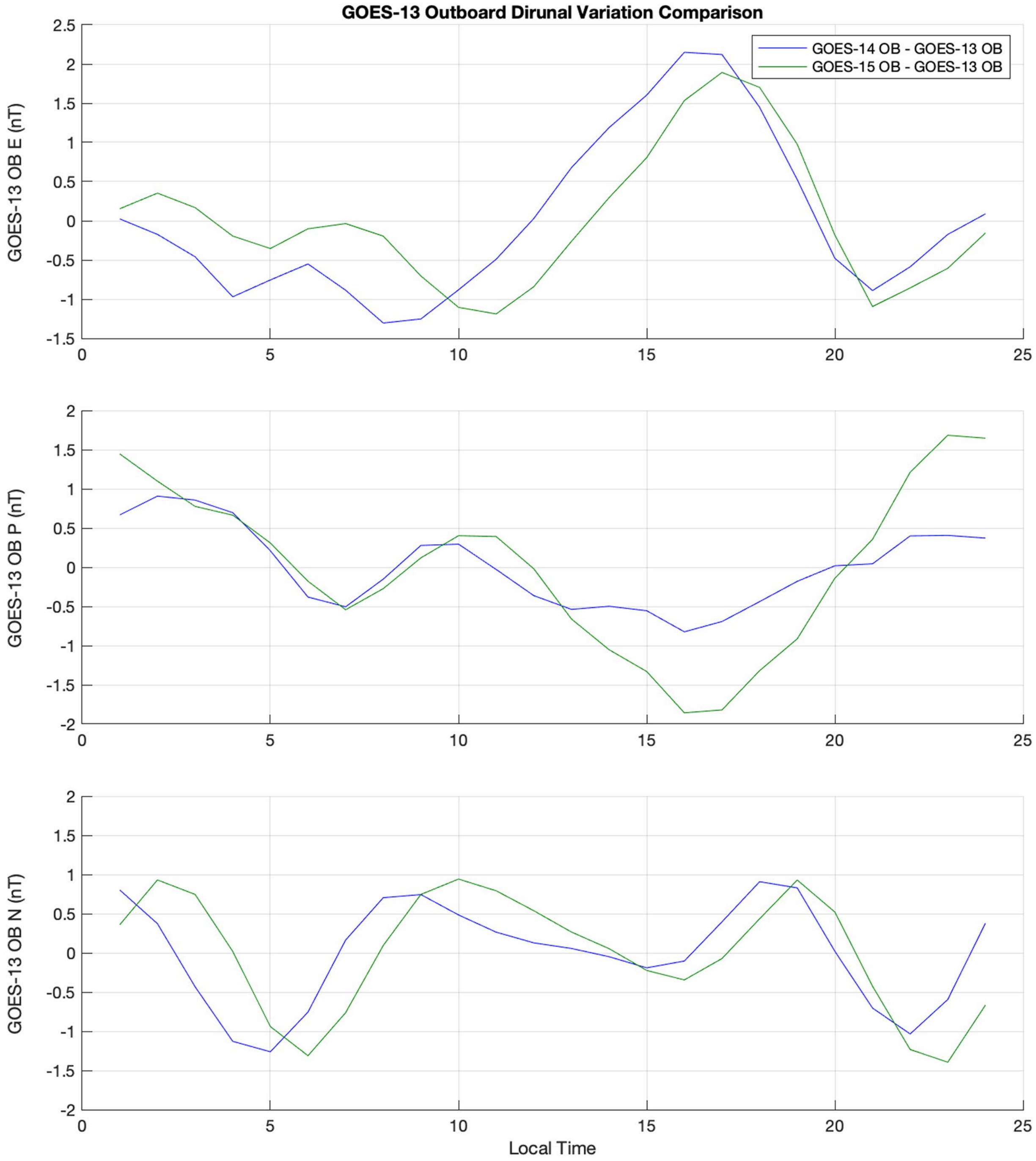

Figure 12. Comparison between GOES-13 outboard magnetometer measurements and GOES-14 and GOES-15 outboard measurements. The TS04 model has been subtracted from all measurements to account for longitudinal separation of the spacecraft.

Figure 12 compares the GOES-13 outboard magnetometer to GOES-14 and GOES-15. There are similar local time variations relative to both GOES-14 and GOES-15—these variations could be explained by either diurnal variations in the GOES-13 outboard magnetometer or mapping errors from the TS04 model. The phase shift in the diurnal pattern may be an artifact of the local time differences of the spacecraft, as the reference local time was selected using the GOES-13 spacecraft location. Given the ambiguity of relative measurements, our interpretation is that all of the GOES-NOP outboard magnetometers are diurnally stable to within ∼1–2 nT, and that estimate is an upper bound driven by the uncertainty of the model and mapping between spacecraft at different locations.

6. Conclusions

This study investigated the long-term stability of the GOES-NOP magnetometers from 2013 to 2018 using relative comparisons between inboard and outboard magnetometers on the same spacecraft, comparison to the TS04 magnetic field model, and comparisons between measurements on different spacecraft using TS04 to account for longitudinal separation.

The inboard and outboard magnetometers on GOES-14 are stable relative to each other within approximately 1–2 nT in all components on diurnal, seasonal and annual timescales. GOES-15 inboard and outboard magnetometers show similar stability after correcting for DC bias shifts related to semi-annual yaw flips. The inboard magnetometer on GOES-13 has a large diurnal signal that creates a problem for evaluating the stability of the outboard magnetometer. We addressed this by comparing the GOES-13 magnetometers to the outboard magnetometers on GOES-14 and GOES-15, using the TS04 model to map measurements between spacecraft. This method independently identified the large diurnal trend in the GOES-13 inboard magnetometer, and showed that the GOES-13 outboard magnetometer has similar stability to the GOES-14 and GOES-15 magnetometers.

The individual magnetometers were also evaluated directly against the TS04 magnetic field model, and the results were consistent with the conclusion that all of the GOES-NOP magnetometers (except GOES-13 inboard) have relatively stable long-term biases. Seasonal variations in the model comparison suggest that there may be small seasonal errors in TS04 (~5 nT). Despite the uncertainties in the TS04 model and mapping between spacecraft separated by large distances in geostationary orbit, all of the comparisons suggest GOES-NOP bias stability of 1–2 nT over the 6-year period.

Although no absolute reference exists to prove the accuracy of the measurements, there are many independent measurements and models available to constrain the variability of the measurement error on various timescales. Once calibration stability is established, point estimates of the DC biases through calibration maneuvers or comparison to reliable nearby magnetometers at any point in the mission can be used to correct the measurements.

Data Availability Statement

The GOES-NOP magnetometer data, including the newly released GOES-14 storage mode data, are available at https://www.ncei.noaa.gov/data/goes-space-environment-monitor/access/science/mag/. The TS04 magnetic field model is described at https://ccmc.gsfc.nasa.gov/models/Tsyganenko%20Magnetic%20Field~TS05/.

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References

Acuna, M. H. (2002). Space-based magnetometers. *Review of Scientific Instruments*, *73*(11), 3717–3736. https://doi.org/10.1063/1.1510570

Fraser, B. J., Grew, R. S., Morley, S. K., Green, J. C., Singer, H. J., Loto'aniu, T. M., & Thomsen, M. F. (2010). Storm time observations of electromagnetic ion cyclotron waves at geosynchronous orbit: GOES results. *Journal of Geophysical Research*, *115*(A5), A05208. https://doi.org/10.1029/2009JA014516

Friis-Christensen, E., Lühr, H., & Hulot, G. (2006). Swarm: A constellation to study the earth's magnetic field. *Earth Planets and Space*, *58*(4), 351–358. https://doi.org/10.1186/BF03351933

GOES 13-15 MAGE/PD PITCH ANGLES ALGORITHM THEORETICAL BASIS DOCUMENT. (2014). Retrieved from https://ngdc.noaa.gov/stp/satellite/goes/doc/MAGEPD_PitchAngles_Processing_ATBD_v1.0.pdf

GOES-16 PS-PVR. (2017). Retrieved from https://www.noaasis.noaa.gov/GOES/PS_PVR_GOES16.html

GOES-17 PS-PVR. (2021). Retrieved from https://www.noaasis.noaa.gov/GOES/PS_PVR_GOES17.html

GOES N Data Book. (2006). Retrieved from https://www.nasa.gov/pdf/148080main_GOES-N%20Databook%20with%20Copyright.pdf

Kokubun, S. (1983). Characteristics of storm sudden commencement at geostationary orbit. *Journal of Geophysical Research*, *88*(A12), 10025–10033. https://doi.org/10.1029/ja088ia12p10025

Loto'aniu, T. M., Redmon, R. J., Califf, S., Singer, H. J., Rowland, W., Macintyre, S., et al. (2019). The GOES-16 spacecraft science magnetometer. *Space Science Reviews*, *215*(4), 1–28. https://doi.org/10.1007/s11214-019-0600-3

Magnes, W., Hillenmaier, O., Auster, H. U., Brown, P., Kraft, S., Seon, J., et al. (2020). Space weather magnetometer aboard GEO-KOMPSAT-2A. *Space Science Reviews*, *216*(8), 1–36. https://doi.org/10.1007/s11214-020-00742-2

Nagai, T. (1987). Field-aligned currents associated with substorms in the vicinity of synchronous orbit: 2. GOES 2 and GOES 3 observations. *Journal of Geophysical Research*, *92*(A3), 2432–2446. https://doi.org/10.1029/ja092ia03p02432

Ness, N. F., Behannon, K. W., Lepping, R. P., & Schatten, K. H. (1971). Use of two magnetometers for magnetic field measurements on a spacecraft. *Journal of Geophysical Research*, *76*(16), 3564–3573. https://doi.org/10.1029/ja076i016p03564

Plaschke, F., Auster, H. U., Fischer, D., Fornaçon, K. H., Magnes, W., Richter, I., et al. (2019). Advanced calibration of magnetometers on spin-stabilized spacecraft based on parameter decoupling. *Geoscientific Instrumentation, Methods and Data Systems*, *8*(1), 63–76. https://doi.org/10.5194/gi-8-63-2019

Rodriguez, J. V., Denton, M. H., & Henderson, M. G. (2020). On-orbit calibration of geostationary electron and proton flux observations for augmentation of an existing empirical radiation model.

Russell, C. T., & McPherron, R. (1973). Semiannual variation of geomagnetic activity. *Journal of Geophysical Research*, *78*(1), 92–108. https://doi.org/10.1029/ja078i001p00092

Schnurr, R., Bonalsky, T., Todirita, M., Kronenwetter, J., Early, D., Grotenhuis, M., et al. (2019). Lessons learned from flight observations of the GOES-R magnetometer. In *2019 ESA workshop on aerospace EMC (aerospace EMC)* (pp. 1–6). IEEE.

Singer, H., Matheson, L., Grubb, R., Newman, A., & Bouwer, D. (1996). Monitoring space weather with the GOES magnetometers. In *GOES-8 and beyond* (Vol. 2812, pp. 299–308). SPIE.

Sitnov, M. I., Tsyganenko, N. A., Ukhorskiy, A. Y., & Brandt, P. C. (2008). Dynamical data-based modeling of the stormtime geomagnetic field with enhanced spatial resolution. *Journal of Geophysical Research*, *113*(A7), A07218. https://doi.org/10.1029/2007JA013003

Takahashi, K., Glassmeier, K.-H., Angelopoulos, V., Bonnell, J., Nishimura, Y., Singer, H. J., & Russell, C. T. (2011). Multisatellite observations of a giant pulsation event. *Journal of Geophysical Research*, *116*(A11), A11223. https://doi.org/10.1029/2011JA016955

Tsyganenko, N. A., & Sitnov, M. I. (2005). Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *Journal of Geophysical Research*, *110*(A3), A03208. https://doi.org/10.1029/2004ja010798

Tsyganenko, N. A., & Sitnov, M. I. (2007). Magnetospheric configurations from a high-resolution data-based magnetic field model. *Journal of Geophysical Research*, *112*(A6), A06225. https://doi.org/10.1029/2007ja012260