

Assessing and Ensuring GOES-R Magnetometer Accuracy

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ABSTRACT

The GOES-R magnetometer subsystem accuracy requirement is 1.7 nanoteslas (nT). During quiet times (100 nT), accuracy is defined as absolute mean plus 3 sigma. During storms (300 nT), accuracy is defined as absolute mean plus 2 sigma. Error comes both from outside the magnetometers, *e.g.* spacecraft fields and misalignments, as well as inside, *e.g.* zero offset and scale factor errors. Because zero offset and scale factor drift over time, it will be necessary to perform annual calibration maneuvers. To predict performance before launch, we have used Monte Carlo simulations and covariance analysis. Both behave as expected, and their accuracy predictions agree within 30%. With the proposed calibration regimen, both suggest that the GOES-R magnetometer subsystem will meet its accuracy requirements.

Keywords: magnetometers, calibration, performance, covariance analysis, simulation

1. INTRODUCTION

Like an optical instrument, a magnetometer has noise and calibrations that add error to its measurements. There are zero offsets, *i.e.* biases, misalignments of the whole instrument plus internal ones, *i.e.* non-orthogonalities, and scale factor, *i.e.* gain, errors. The two GOES-R magnetometers are vector magnetometers which measure all three components of the magnetic field.

1.1 Magnetic Environment

To reduce the effect of stray fields, *i.e.* time-varying magnetic fields from the spacecraft, the magnetometers are mounted on a long boom 6.5 and 8.5 meters (m) from the boom base as shown in Figure 1. Having two magnetometers provides redundancy, allows averaging for noise reduction and enables us to solve for stray fields. This last capability called gradiometry is useful if stray fields are much larger than the noise, but this probably will not be the case for GOES-R.



Figure 1. Spacecraft, Boom and Magnetometers

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Even out on the boom, the magnetometers may see stray fields due to the solar array, arcjet thrusters and reaction wheels. All three are expected to be on the order of 0.1 nanoteslas (nT) at the inboard (IB) magnetometer and about half that at the outboard (OB) magnetometer. We may pre-process magnetometer observations to correct for some of these so that what remains is close to being white noise with 0.1 nT standard deviation.

At geostationary altitude, the magnetometers see fields about five hundred times smaller than those at the Earth's surface, *i.e.* 100 nT rather than 50 μ T. Figure 2 shows fields for a quiet and a storm day. Fields routinely vary by 10% on quiet days but during storms can vary by 200% or more. For this reason, our magnetometer measurement range goes from -512 to +512 nT. Resolution is 0.016 nT, and root mean square noise is under 0.1 nT.

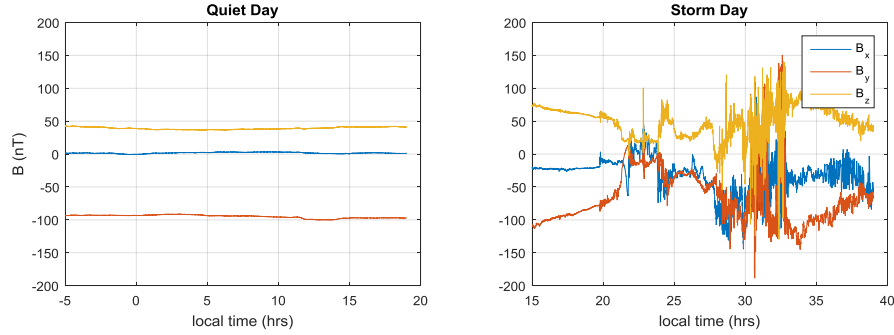


Figure 2. Quiet and Storm Day Fields

1.2 Error Sources

From ground calibration, zero offsets are well-known at launch but may drift over time due to aging of electronics components, *e.g.* resistors. Although not well-documented, the commonly accepted “rule of thumb” is that zero offsets drift by 0.2 nT/ $\sqrt{\text{yr}}$. They do so as a random walk with variance growing linearly with time and standard deviation growing as the square root of time.

Misalignments come from launch shock, thermal deformation and manufacturing. Launch shock refers to the mechanical vibrations during launch and can cause 1° misalignments. After deployment, the boom is heated and cooled by the Sun which causes the inboard magnetometer to rotate up to 0.15° and the outboard magnetometer to rotate up to 0.10° with respect to it. There are also constant sensor axis internal misalignments on the order of 1° but which are known to 0.1°.

Like zero offsets, scale factor errors are known at launch but may drift over time. Although scale factor drift is also due to changing resistor values, we know of no “rule of thumb” corresponding to that for zero offset. Worst case analyses predict 0.4% maximum drift over the 15-year mission lifetime which translates to a drift rate of 0.1%/ $\sqrt{\text{yr}}$.

1.3 Algorithms and Requirements

For these expected noise and stray fields, using the gradiometer algorithm would worsen the noise more than it would reduce the stray fields.¹ The algorithm we will probably use to estimate the ambient field \vec{B}^A is simple averaging of the inboard \vec{B}^{IB} and outboard \vec{B}^{OB} readings

$$\vec{B}^A = (\vec{B}^{IB} + \vec{B}^{OB})/2 \quad (1)$$

The GOES-R magnetometer subsystem is required to provide ambient field measurements with absolute mean plus 2 or 3 standard deviations (σ) error less than 1.7 nT per axis. Although it is not specified, we have assumed that this statistic is computed over a day. For “quiet” days, it is 3σ , and for storms it is 2σ .

$$\text{Quiet } |\mu| + 3\sigma \leq 1.7 \text{ nT} \quad (2)$$

$$\text{Storm } |\mu| + 2\sigma \leq 1.7 \text{ nT} \quad (3)$$

2. ANALYSIS

It's hard to know if the magnetometer subsystem will meet its requirements or not. Whether it is before or after launch, we can only guess at the sources of error. On the ground we can in principle measure things but they are not really “flight-like”. On-orbit, they are flight-like but we can't get to them to measure them. For now, all we can do is use our models and ground measurements to make predictions. On orbit, we'll need ways to infer performance from the real data.

There are two methods for predicting performance that immediately come to mind. One is Monte Carlo simulation, and the other is covariance analysis. Simulation is the more flexible of the two but takes a lot of computation time and does not provide much insight into what is happening. How to combine the results of the many trials can also be a contentious question.

Covariance analysis is like the spreadsheet error budgets we use for most everything except that by starting with a mathematical model, it does not leave out any interactions. A partial covariance estimate that accounts for observation noise comes from analytically solving any least squares problem such as the averaging algorithm, but to get more realistic answers it is essential to include consider parameters, *i.e.* those not solved for and known with limited accuracy.²

Rather than choose between simulation and covariance, we have implemented both in the hope that their agreement lends further credence to the results.

2.1 Calibration Maneuvers

Over the mission, zero offset standard deviation is expected to grow to 0.77 nT. Scale factor error in a quiet field may reach 0.38 nT. These are large compared to the 1.7 nT specification. On a quiet day, the scale factor error simply adds to the mean error. On a storm day, however, scale factor error is three times larger due to stronger fields and due to field variability adds to error standard deviation which gets doubled in the performance metric.

For these reasons, it was considered necessary to plan for annual calibration maneuvers. Although one might like to perform 180° slews about each axis, reaction wheel torque and communications constraints limit how far we may deviate from nadir pointing. As illustrated in Figure 3, the current maneuver goes 30° off-nadir and takes 22 minutes. The spacecraft rotates about multiple body axes which enables us to solve for both zero offsets and misalignments.

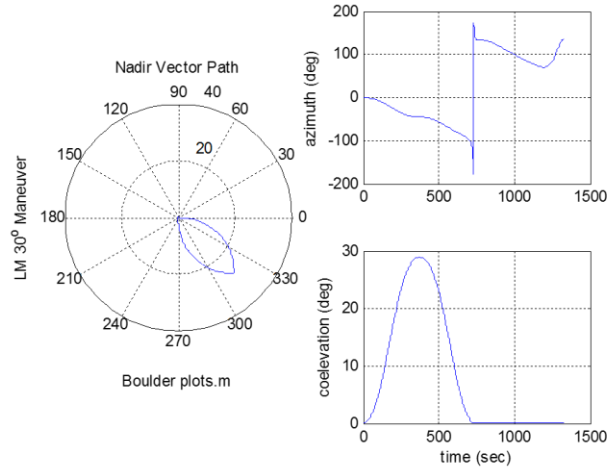


Figure 3. Calibration Maneuver

The calibration algorithm assumes the ambient field to be constant, and any field change introduces error. An empirical criterion for rejecting a maneuver span is to look at the root sum square of the ambient field components change in orbital coordinates δB

$$\delta B = \sqrt{\Delta B_x^2 + \Delta B_y^2 + \Delta B_z^2} \quad (4)$$

It was found from simulations that if δB exceeded 0.3 nT, calibration error was significantly worse than when it did not.³

2.2 Observation Model

The observation model predicts the inboard and outboard magnetometer readings as functions of field and calibration parameters. The parameters we include are:

1. ambient magnetic field \vec{B}^A in orbital coordinates
2. spacecraft magnetic field \vec{B}^S in spacecraft body coordinates
3. zero offsets for two magnetometers $\vec{b}^{IB}, \vec{b}^{OB}$ in magnetometer coordinates
4. inboard magnetometer misalignment \vec{m}^{IB} in inboard magnetometer coordinates
5. inboard-to-outboard magnetometer relative misalignment \vec{m}^{rel} in inboard magnetometer coordinates
6. scale factor errors for two magnetometers $\vec{k}^{IB}, \vec{k}^{OB}$
7. non-orthogonality (internal misalignments) for two magnetometers $\vec{n}^{IB}, \vec{n}^{OB}$ in magnetometer coordinates

Because the magnetometers are both on the boom, the outboard misalignment is the sum of the inboard misalignment plus an inboard-to-outboard relative misalignment. Outboard alignment depends on inboard alignment, so the two are not independent. To avoid this complication, we use as misalignment parameters the spacecraft-to-inboard and inboard-to-outboard relative misalignments. This keeps all the parameters independent.

Altogether there are 30 possible solve-for and consider parameters which we bundle in a vector \vec{X}

$$\vec{X}^T = (\vec{B}^A{}^T \quad \vec{B}^S{}^T \quad \vec{b}^{IB}{}^T \quad \vec{b}^{OB}{}^T \quad \vec{m}^{IB}{}^T \quad \vec{m}^{rel}{}^T \quad \vec{k}^{IB}{}^T \quad \vec{k}^{OB}{}^T \quad \vec{n}^{IB}{}^T \quad \vec{n}^{OB}{}^T) \quad (5)$$

Assuming for simplicity that the magnetometers are nominally aligned with spacecraft body coordinates, the observation model is

$$\begin{pmatrix} \vec{B}^{IB} \\ \vec{B}^{OB} \end{pmatrix} = \begin{pmatrix} (I_3 + K^{IB})M^{IB}(A_{bo}\vec{B}^A + \vec{B}^S) \\ (I_3 + K^{OB})M^{OB}(A_{bo}\vec{B}^A + \alpha\vec{B}^S) \end{pmatrix} + \begin{pmatrix} \vec{b}^{IB} \\ \vec{b}^{OB} \end{pmatrix} + \begin{pmatrix} \vec{v}^{IB} \\ \vec{v}^{OB} \end{pmatrix} = \vec{h} \quad (6)$$

The other quantities in the model are described below:

- Attitude matrix A_{bo} transforms the ambient field from orbital to body, *i.e.* nominal magnetometer, coordinates.
- Scale factor matrix K is diagonal and is computed from the three scale factor errors for each magnetometer

$$K = \begin{pmatrix} k_u & 0 & 0 \\ 0 & k_v & 0 \\ 0 & 0 & k_w \end{pmatrix} = \hat{k} \quad (7)$$

The scale factor vector \vec{k} is

$$\vec{k}^T = (k_u \quad k_v \quad k_w) \quad (8)$$

- Misalignment matrix M transforms the ambient field from body to magnetometer coordinates and is made up of the three misaligned sensor axes \hat{u} , \hat{v} and \hat{w}

$$M = (\hat{u} \quad \hat{v} \quad \hat{w})^T \quad (9)$$

Misalignment angles ϕ_i , θ_i and ψ_i represent the x, y and z components of the sensor axis rotation vectors. For small angles, M may be approximated as

$$M = (\hat{u} \quad \hat{v} \quad \hat{w})^T \approx \begin{pmatrix} 1 & \psi_u & -\theta_u \\ -\psi_v & 1 & \phi_v \\ \theta_w & -\phi_w & 1 \end{pmatrix} = I - \tilde{m} + \tilde{n} \quad (10)$$

- Antisymmetric matrix \tilde{m} is

$$\tilde{m} = \begin{pmatrix} 0 & -(\psi_u + \psi_v)/2 & (\theta_w + \theta_u)/2 \\ (\psi_u + \psi_v)/2 & 0 & -(\phi_v + \phi_w)/2 \\ -(\theta_w + \theta_u)/2 & (\phi_v + \phi_w)/2 & 0 \end{pmatrix} \quad (11)$$

where the bulk misalignment vector \vec{m} is the average of the axis misalignments

$$\vec{m}^T = (\phi_v + \phi_w \quad \theta_w + \theta_u \quad \psi_u + \psi_v)/2 \quad (12)$$

- Symmetric matrix \tilde{n} is

$$\tilde{n} = \begin{pmatrix} 0 & (\psi_u - \psi_v)/2 & (\theta_w - \theta_u)/2 \\ (\psi_u - \psi_v)/2 & 0 & (\phi_v - \phi_w)/2 \\ (\theta_w - \theta_u)/2 & (\phi_v - \phi_w)/2 & 0 \end{pmatrix} \quad (13)$$

where the non-orthogonality vector \vec{n} is half the differences of the corresponding misalignments

$$\vec{n}^T = (\phi_v - \phi_w \quad \theta_w - \theta_u \quad \psi_u - \psi_v)/2 \quad (14)$$

The partition of the ψ misalignments into bulk misalignment and non-orthogonality is illustrated in Figure 4.

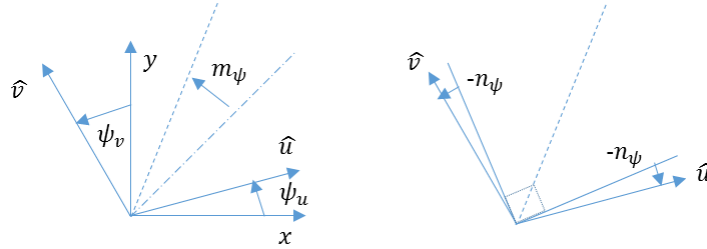


Figure 4. Bulk Misalignment / Non-Orthogonality Partition Example

- The scalar α comes from the gradiometer stray field model and is equal to the cube of the outboard-to-spacecraft distance r^{OB} over the inboard-to-spacecraft distance r^{IB} ratio

$$\alpha = (r^{OB}/r^{IB})^3 \quad (15)$$

It relates the stray field at the outboard magnetometer to that at the inboard magnetometer, *i.e.* \vec{B}^S . This model assumes that the magnetometers are far from the spacecraft.

- Noise \vec{v} is simulated as a zero mean Gaussian random variable with specified standard deviation. Diurnal misalignments are modeled as zero mean uniformly-distributed random variables limited by the boom deformation requirements.

2.3 Simulation

In principle, simulation is easy. One assumes parameter values, plugs them into the observation model, computes the least squares solution and then sees how large the error is. How one connects and combines them, however, makes a difference. We ran multiple 15-year missions, averaged them to get performance as a function of time over those 15 years and reported the value of the End-of-Life (EOL) performance metric.

If the magnetometer observations were linear functions of the solve-for parameters \vec{x} , the minimum variance weighted least squares solution would be

$$\vec{x} = (H_x^T W H_x)^{-1} H_x^T W \vec{y} \quad (16)$$

where H_x is the observation derivative

$$H_x = \frac{\partial \vec{h}}{\partial \vec{x}} \quad (17)$$

\vec{y} is the observation vector, and W is the minimum variance (σ_y^2) weighting matrix

$$W = \frac{1}{\sigma_y^2} I \quad (18)$$

In normal operations when we solve only for the ambient field, this is the solution. During calibration, we also solve for zero offsets and misalignments. Because the observations depend nonlinearly on the misalignments, it is necessary to iterate on the solution

$$\vec{x} \leftarrow \vec{x} + (H_x^T W H_x)^{-1} H_x^T W \vec{z} \quad (19)$$

When iteration is necessary, \vec{y} is replaced by the residual or innovation \vec{z} which is the difference between the observation vector \vec{y} and the model prediction \vec{h} as computed from the current parameter estimate \vec{x}

$$\vec{z} = \vec{y} - \vec{h}(\vec{x}) \quad (20)$$

How many iterations are necessary depends on the accuracy desired. As part of the process, one gets an estimate of the solution covariance P_x that thanks to W reflects the contribution of the observation noise

$$P_x = (H_x^T W H_x)^{-1} \quad (21)$$

For normal operations, *i.e.* averaging, \vec{x} only includes the ambient field

$$\vec{x} = \vec{B}^A \quad (22)$$

For calibration, \vec{x} includes the ambient field, zero offsets and bulk misalignments

$$\vec{x}^T = (\vec{B}^A{}^T \quad \vec{b}^{IB}{}^T \quad \vec{b}^{OB}{}^T \quad \vec{m}^{IB}{}^T \quad \vec{m}^{rel}{}^T) \quad (23)$$

We calibrate immediately after launch, evaluate daily performance at monthly intervals and optionally calibrate once a year thereafter. If we are doing quiet days, we compute the absolute mean plus 3 sigma error for each day, average them over the missions and report the EOL value. For storms, we compute the absolute mean plus 2 sigma error.

In computing each day's error metric, we took 100 samples with:

1. random noise and misalignments
2. simulated zero offsets and scale factors
3. current zero offset and misalignment estimates

This assumes that performance is worst at EOL which is expected because scale factor has then had the most time to drift. What we deliberately did not do was to take the metric of EOL metrics or worst case of EOL metrics. This would be overly conservative and would likely turn a 3 sigma number into something like a 5 sigma number.

Depending on the ambient fields used, performance can be different. For calibration, we used quiet day data from GOES-12. For quiet day performance, we used a nominal 100 nT field largely directed in the southern direction. For storm day performance, however, we simulated random fields up to 300 nT magnitude pointing in all directions. We felt that this was a conservative but realistic choice of fields.

2.4 Consider Covariance

The least squares solution provides an estimate of the covariance matrix P_x that includes the effect of Gaussian observation noise but assumes that all other parameters not being solved-for are perfectly known. If those parameters \vec{c} are not perfectly known, we can add a “consider” covariance P_c that accounts for those uncertainties. The total covariance P is the sum of these two contributions

$$P = P_x + P_c \quad (24)$$

Consider covariance P_c is just a transformation of the consider parameter covariance P_{c0} to the solve-for parameters. A derivation follows:

- If the consider parameters themselves have covariance P_{c0} , their contribution to the total covariance is of the form

$$P_c = TP_{c0}T^T \quad (25)$$

where T transforms consider parameter uncertainty $\sigma_{\vec{c}}$ to solve-for parameter uncertainty $\sigma_{\vec{x}}$

$$\sigma_{\vec{x}} = \frac{\partial \vec{x}}{\partial \vec{c}} \sigma_{\vec{c}} = T \sigma_{\vec{c}} \quad (26)$$

- If H_c is the observation derivative with respect to the consider parameters

$$H_c = \frac{\partial \vec{h}}{\partial \vec{c}} \quad (27)$$

the observation uncertainty $\sigma_{\vec{h}}$ due to consider parameter uncertainty is

$$\sigma_{\vec{h}} = \frac{\partial \vec{h}}{\partial \vec{c}} \sigma_{\vec{c}} \quad (28)$$

- The linear least squares solution is itself a transformation of observations to solve-for parameters

$$(H_x^T W H_x)^{-1} H_x^T W = P_x H_x^T W = \frac{\partial \vec{x}}{\partial \vec{y}} \quad (29)$$

- Because \vec{h} models \vec{y} , $\frac{\partial \vec{x}}{\partial \vec{h}}$ is the same as $\frac{\partial \vec{x}}{\partial \vec{y}}$, and T becomes

$$T = \frac{\partial \vec{x}}{\partial \vec{c}} = \frac{\partial \vec{x}}{\partial \vec{h}} \frac{\partial \vec{h}}{\partial \vec{c}} = \frac{\partial \vec{x}}{\partial \vec{y}} \frac{\partial \vec{h}}{\partial \vec{c}} = P_x H_x^T W H_c \quad (30)$$

With the covariance approach, one doesn't actually solve for ambient field. There is no solution and so one cannot compute an error. All we have is the standard deviation which comes from the covariance matrix. Assuming that the averaging estimator is unbiased so that its mean error is zero, we simply multiply the standard deviation by 2 or 3 depending on whether it is a quiet or storm day as use that as the performance metric.

2.5 Observation Derivatives

We need observation partial derivatives with respect to the field and calibration parameters both to solve the least squares problem in the simulation and to compute the consider covariance. Because both can be solved as linear, we only need first-order approximations of the partials. Derivations are sketched out below:

- Given the observation model above, the derivatives of the inboard magnetometer readings with respect to the ambient and stray fields and with respect to the zero offsets are simply the identity matrix

$$\frac{\partial \vec{B}}{\partial \vec{B}^A} = \frac{\partial \vec{B}}{\partial \vec{B}^s} = \frac{\partial \vec{B}}{\partial \vec{b}} = I_3 \quad (31)$$

Those for the outboard magnetometer are the same except that the stray field derivative is αI_3 .

- The derivative with respect to scale factor errors is the diagonal matrix \vec{B}

$$\frac{\partial \vec{B}}{\partial \vec{k}} = \frac{\partial}{\partial k} \begin{pmatrix} k_u B_u \\ k_v B_v \\ k_w B_w \end{pmatrix} = \begin{pmatrix} B_u & 0 & 0 \\ 0 & B_v & 0 \\ 0 & 0 & B_w \end{pmatrix} = \vec{B} \quad (32)$$

- The derivative with respect to bulk misalignment is the anti-symmetric matrix \vec{B}

$$\frac{\partial \vec{B}}{\partial \vec{m}} = \frac{\partial}{\partial m} (-\vec{m} \vec{B}) = \frac{\partial}{\partial m} \begin{pmatrix} -m_2 B_w + m_3 B_v \\ m_1 B_w - m_3 B_u \\ -m_1 B_v + m_2 B_u \end{pmatrix} = \begin{pmatrix} 0 & -B_w & B_v \\ B_w & 0 & -B_u \\ -B_v & B_u & 0 \end{pmatrix} = \vec{B} \quad (33)$$

- The derivative with respect to the non-orthogonality is the symmetric matrix \vec{B}

$$\frac{\partial \vec{B}}{\partial \vec{n}} = \frac{\partial}{\partial n} (\vec{n} \vec{B}) = \frac{\partial}{\partial n} \begin{pmatrix} n_3 B_v + n_2 B_w \\ n_3 B_u + n_1 B_w \\ n_2 B_u + n_1 B_v \end{pmatrix} = \begin{pmatrix} 0 & B_w & B_v \\ B_w & 0 & B_u \\ B_v & B_u & 0 \end{pmatrix} = \vec{B} \quad (34)$$

The derivative matrix H is then

$$H = \frac{\partial \vec{h}}{\partial \vec{x}} = \begin{pmatrix} A_{bo} & I_3 & I_3 & 0_3 & \vec{B}^{IB} & 0_3 & \vec{B}^{IB} & 0_3 & \vec{B}^{IB} & 0_3 \\ A_{bo} & \alpha I_3 & 0_3 & I_3 & \vec{B}^{OB} & \vec{B}^{OB} & 0_3 & \vec{B}^{OB} & 0_3 & \vec{B}^{OB} \end{pmatrix} \quad (35)$$

3. RESULTS

As discussed above, there are different performance requirements for quiet and storm days. Quiet day results are tabulated in Table 1 and are shown in Figure 5. With annual calibration, the EOL error is well below the 1.7 nT limit. Maximum error on any axis is 0.81 nT. Agreement between the simulation and covariance results is better than 27% with the simulated errors always the larger of the two. Without annual calibration, the maximum per axis error reaches 1.95 nT.

Table 1. Quiet Day EOL Errors

Quiet	B _x	B _y	B _z
Annual Cal			
sim	0.81	0.56	0.62
cov	0.59	0.54	0.57
(sim-cov/pct)	0.22/27%	0.02/4%	0.05/8%
PLT-only Cal			
sim	1.95	1.71	1.80
cov	1.70	1.68	1.69
(sim-cov/pct)	0.25/13%	0.03/2%	0.11/6%

The quiet day results are better than might be expected in light of the scale factor drift and meet the original 1.0 nT requirement that was relaxed to 1.7 nT. One reason for this is the fact that we evaluate quiet day performance in fields similar to those used for calibration. It may be that because the zero offset and scale factor errors are not distinguishable under such conditions, and the zero offset error compensates for the scale factor error.

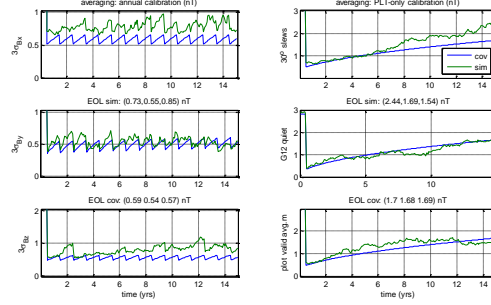


Figure 5. Quiet Day Performance

Storm day results are tabulated in Table 2 and are shown in Figure 6. With annual calibration, they still remain under the 1.7 nT limit, but the maximum per-axis error now reaches 1.34 nT. The poorer performance is likely due to applying quiet day calibrations to storm fields. Again, worst case simulation covariance agreement is 27% with the simulation results still the more pessimistic of the two. Without annual calibration, the maximum per-axis error reaches 1.85 nT.

Table 2. Storm Day EOL Errors

Storm	B_x	B_y	B_z
Annual Cal			
sim	1.34	1.15	1.26
cov	0.98	0.95	0.93
(sim-cov/pct)	0.36/27%	0.20/17%	0.33/26%
PLT-only Cal			
sim	1.85	1.61	1.63
cov	1.44	1.42	1.41
(sim-cov/pct)	0.41/22%	0.19/12%	0.22/14%

While running more mission simulations might help the quiet day covariance-simulation agreement, the poorer storm day agreement does not seem to be due to lack of data. The simulation averages parallel the covariance and are relatively smooth. Interestingly, annual quiet day calibration does not help storm day performance much if at all. For both quiet and storm days, the largest errors are in B_x where the *pct* discrepancy is 27%

$$pct = 100\% \times \frac{sim-cov}{sim} \leq 27\% \quad (36)$$

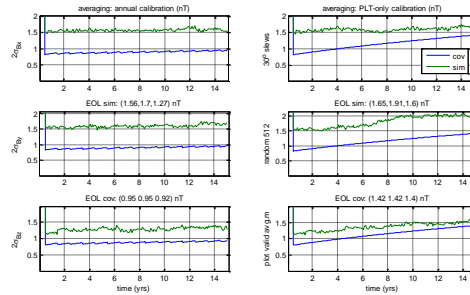


Figure 6. Storm Day Performance

By taking the conventional approach to calibration in which one assumes that the ambient field remains constant over the maneuver, we limit ourselves to calibrating on quiet days. This makes scale factor errors look like zero offsets which corrupts zero offset estimates. Although this may help quiet day accuracy by compensating for the scale factor errors, those zero offset errors reduce the accuracy on storm days.

If one could calibrate on storm days, it might be possible to decouple the zero offset and scale factor errors. The problem is that one could not assume a constant field over the calibration period. There is, however, a zero offset calibration scheme that does not require maneuvers or constant fields.⁴ Initial indications suggest that it may not provide the necessary accuracy, but it should be further investigated in light of its potential benefits.

4. CONCLUSIONS

In this paper, we have tried to predict GOES-R magnetometer subsystem performance on quiet and storm days using covariance analysis and simulations. The per-axis accuracy requirement is 1.7 nT for both cases although the accuracy is defined as absolute mean plus 3 sigma error for quiet days and absolute mean plus 2 sigma error for storm days. The results from the two methods agree to 30% with the simulation results consistently the more pessimistic of the two. With annual calibration, both predict quiet day accuracy better than 1.0 nT and storm day accuracy better than 1.5 nT. Without annual calibration, both predict quiet and storm day accuracy worse than 1.7 nT. Thus, it seems that annual calibration is both sufficient and necessary for the GOES-R magnetometer subsystem to meet its accuracy requirements.

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