MESSENGER Propulsion Latching Valve Magnetic Moment Measurements

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1.0 Objectives

The MESSENGER magnetic fields science investigation requires spacecraft magnetic contamination fields lower than ~1 nT for fixed fields and 0.03 nT for variable fields. Since magnetic latching valves are used extensively in the propulsion system, characterizing and if necessary canceling the field from this system is a high priority. The objective of the tests described here was to accurately measure the magnetic moments of latching valves used in the MESSENGER propulsion system to specify the design of a compensation magnet. The most mass effective way to mitigate the magnetic fields of the propulsion valves is to include a compensation magnet as part of the propulsion system which would be designed to cancel the field produced by all of the valves at the location of the MESSENGER magnetometer. Because the science magnetometer is separated from the propulsion system by ~ 4m (3.6m long boom) while the valves are separated from each other by less than 1m, a single compensation magnet integrated in the propulsion valve assembly will be sufficient, that is, compensating each valve individually is unnecessary. To alleviate the need to magnetically survey the MESSENGER spacecraft or the assembled propulsion system, it was decided to accurately characterize each magnetic latching valve individually, calculate the net magnetic field given the valve locations, and design a compensation magnet based on this information. Initial estimates based on similar valves flown on the NEAR spacecraft, indicated that the field at the MESSENGER magnetometer due to the propulsion valves would be ~30 nT. Cancellation to ~1 nT requires that the net magnetic moment be determined to 3%.

2.0 Description of Measurements

The MESSENGER propulsion system uses 6 3/8" diameter latching valves (Moog model #52-266), 1 1/4" latching valve (Vacco V1E10470-01), and two high pressure latch valves (Valcor V27200-818-1). All of the flight valves and one spare of each valve type were transported to JHU/APL for magnetic characterization.

2.1 Facilities

The JHU/APL magnetics facility is a steel-free building located not closer than 300 yards to the nearest large facility structure or regularly used roadway. (Figure 1) A set of 6 foot dia Helmholtz coils are housed in this building (Figure 2). Every valve was placed near (within 20 cm) of the center of this coil system in a nearly null field region to minimize spurious Earth-induced fields. A non-magnetic (aluminum and brass) turntable is located at the center of the coils and was used to rotate the valves under test. The table and coils were assembled to be level to within 0.08°. Angular accuracy in knowledge and reproducibility was estimated to be ~0.2° comparable to the thickness of scribe lines at the table perimeter. A new set of power electronics has been assembled to allow computer control of the coil currents and although the software control was not fully implemented at the time of these tests, the coil system and electronics was used to cancel the Earth's field to within 1%.

Magnetic field measurements were made with a Billingsley LFM-100 fluxgate magnetometer, ±100,000 nT range, ±1/2% linearity, sampled at 1kHz with a 16 bit A/D and logged onto a laptop PC using LabView. The same magnetometer system will be used in the design, construction and test of the propulsion system compensation magnet.

2.2 Geometry

To achieve accurate knowledge of the moments, careful specification of the orientation and location of the latch valves was essential. A reference coordinate system was adopted defined by the Helmholtz coil system, Z vertically upward, Y positive toward the facility doors and X right to left facing the entrance to the facility. The origin of this system was chosen to be the center of the turntable top.

A fixture consisting of aluminum plates configured in a box open on two sides was built to which each of the valves were attached with screws (Figure 3). The box allows one to place the valve on the table with any of the six sides facing down (Figure 4). An arbitrary fixture coordinate system was adopted and noted on every face of the fixture. One corner of the box was chosen as the fixture origin. For each of the six orientations of the fixture on the table, the position of the fixture reference corner and the direction of each XYZ-fixture unit vectors were recorded in facility coordinates for a table rotation angle of 0°.

The orientation of the valve relative to the fixture was controlled to better than 0.1° (determined by the bolt hole pattern) and relative to the table better than 0.2° (controlled by lining up edges of the box fixture with diameter scribe lines on the table). The location of the fixture with respect to the center of the table top was measured to within ±0.5mm and used as the moment location for preliminary immediate analyses.

The location of the effective magnetic moment in each valve is treated as an unknown in the analysis. To obtain an approximate rapid estimate of the magnetic moment the location of the valve body center was noted to within ±0.5mm. This position is expressed in fixture coordinates relative to the fixture origin.

The magnetometer was positioned on an aluminum box channel mounted to a tripod. The level of the magnetometer was adjusted to better than 0.5° and one corner of the magnetometer was chosen as the reference point (Figure 5). The location of the reference point relative to the center of the table top was measured to within ±0.5mm. The magnetometer alignment was chosen so that the XYZ axes of the instrument matched the facility coordinate system.

The ring core magnetometer does not have exactly coincident active sensing elements. The separation of the sensing elements in the magnetometer was ~2cm, the Y and Z ring cores being closer to the table center than the X axis ring core center. The distance between the magnetometer sensor and the table top center was ~40cm. Hence, the 2cm difference in location of the ring cores would lead to a (2/40)*3 = 15% discrepancy between the Y/Z and X measurements for the same dipole moment. The centers of each ring core axis was therefore measured relative to the reference corner of the magnetometer to within ±0.5mm.

2.3 Test Procedures

For each valve, six series of measurements were conducted, one series for each of six orientations of the valve fixture on the table (cf. Figure 4). Each series, denoted as a 'run', consisted of a continuous time series of magnetic field measurements. Each run starts with the valve removed from the table in the farthest corner of the room, proceeds with 13 orientations of the table spaced at 30° increments (Figure 7) with the valve placed on the table (0° was repeated), and ends with the valve returned to the farthest corner of the room. Each table angle was maintained for approximately 5 seconds so that the data from a run consisted of a series of steps (Figure 7). The signal from the valve removed from the coils (assessed by rotating the valve when removed) was not detectable against the noise of the magnetometer and residual noise in room (approximately ±1.5 , ±3 and ±4 nT 1-sigma in X, Y and Z respectively).

For every run a digital picture was taken of the valve orientation in the 0° table angle position (cf. Figure 4). The valve model number and serial number were recorded in each picture. To ensure that the same orientation was actually used for the run (when replacing the valve fixture after removing it to start the run) a note was attached to the fixture indicating up and the direction to the magnetometer.

The series of six runs provides measurements of the magnetic field covering the sphere around the valve. In principle one can determine the moment using only two magnetic field measurements but this assumes that one knows the precise location of the magnetic moment. Since the objective is to specify the magnetic moment with high accuracy, the uncertainty in the moment location made it necessary to conduct the more exhaustive measurements described here.

The configuration of the valves, that is, 'open' or 'closed' were verified at JHU/APL at the time of the tests by testing continuity of the internal micro-switch of each valve. Valves 52-266 and V27200-818-1 will be 'closed' during normal operations and were tested in the 'closed' position. Valves V1E10470-01 will be 'open' during normal operations and were tested in the 'open' position. Initially, the V27200-818-1 valves were tested in the 'open' position. This was discovered at JHU/APL in time to change their position to 'closed' and re-measure the valve moments.

2.4 Initial Analysis

The magnetic field at each table angle was evaluated by taking the average of magnetic field readings on each step (Figure 7). The zero level was calculated as the average of the levels with the valve removed from the table. The net field due to the valve is then the difference between the field in each step and this zero level. The zero levels were reproducible to within ±5 nT. For each valve, this analysis yields 72 vector measurements. Initial results for the valve moments were evaluated as soon as all of the measurements for each valve were completed (Figure 8).

This allowed us to check whether the measurements were free of outliers (indicating an error in the tests) and of sufficiently low noise to allow a good moment determination.

3.0 Analysis and Results

3.1 Mathematical Framework and Solution Method

The magnetic field of the jth component, B_j, (where j = X, Y or Z) is given by the position of the moment, $\mathbf{r}_\mu$, the measurement point, $\mathbf{r}_{p,j}$, (which is not necessarily the same for all magnetometer axes) and the magnetic moment, $\boldsymbol{\mu}$. Care must be taken to properly account for the coordinate system in which each quantity is expressed. Let $\boldsymbol{\mu}^*$ be the magnetic moment in facility coordinates and $\mathbf{r}_\mu^*$ be the position of the moment relative to the facility coordinate origin. If we let $\underline{\mathbf{T}}$ be the transformation matrix between valve fixture coordinates and facility coordinates for a facility table angle of 0°, and $\underline{\mathbf{R}}(\theta)$ be the rotation matrix of X-Y facility coordinates corresponding to a table rotation of an angle θ, then $\boldsymbol{\mu}^* = \underline{\mathbf{R}}(\theta)\cdot\underline{\mathbf{T}}\cdot\boldsymbol{\mu}$ and $\mathbf{r}_p^* = \underline{\mathbf{R}}(\theta)\cdot\underline{\mathbf{T}}\cdot\mathbf{r}_p$. Note than $\underline{\mathbf{T}}$ is different for each run while $\underline{\mathbf{R}}(\theta)$ is different for each θ. Then B_j is j^{th} component of

$$\mathbf{B}_j = \left(3(\mathbf{r}_{p,j} - \mathbf{r}_\mu^*)\, [(\mathbf{r}_{p,j} - \mathbf{r}_\mu^*)\cdot\boldsymbol{\mu}^*] - |\mathbf{r}_{p,j} - \mathbf{r}_\mu^*|^2\, \boldsymbol{\mu}^*\right) / \left(| \mathbf{r}_{p,j} - \mathbf{r}_\mu^*|^5 \right) \qquad (1)$$

where [$\mathbf{B}$]=nT, [$\mathbf{r}$]=meters and [$\boldsymbol{\mu}$]=nT-m^3. It is convenient to define the operator

$$\underline{\mathbf{A}}_j = \{1/(| \mathbf{r}_{p,j} - \mathbf{r}_\mu^*|^5) \}(3(\mathbf{r}_{p,j} - \mathbf{r}_\mu^*)(\mathbf{r}_{p,j} - \mathbf{r}_\mu^*) - |\mathbf{r}_{p,j} - \mathbf{r}_\mu^*|^2\, \underline{\mathbf{I}})\underline{\mathbf{R}}(\theta)\underline{\mathbf{T}} \qquad (2)$$

such that

$$\mathbf{B}_j = \underline{\mathbf{A}}_j\, \boldsymbol{\mu} \qquad (3)$$

This form expresses $\mathbf{B}_j$ in terms of $\boldsymbol{\mu}$ rather than $\boldsymbol{\mu}^*$. The magnetometer readings were organized in a 12*6*3 = 216 element vector, $\mathcal{B}$, consisting of all of the magnetic field readings for a given valve (12 steps, 6 runs, 3 axes). Corresponding to this vector, a 216 row 3 column operator, $\underline{\mathcal{A}}$, was constructed from (2) so that

$$\mathcal{B} = \underline{\mathcal{A}}\, \boldsymbol{\mu} \qquad (4)$$

The moment was solved by inverting (4) using singular value decomposition. Denoting the fit moment as $\boldsymbol{\mu}_{fit}$, the residual, $\delta\mathcal{B} = \mathcal{B} - \underline{\mathcal{A}}\cdot\boldsymbol{\mu}_{fit}$ was used to measure the error using the normalized form

$$\Delta = \sqrt{(\delta\mathcal{B}\cdot\delta\mathcal{B} / \mathcal{B}\cdot\mathcal{B})} \qquad (5)$$

The position offset of the moment was found by minimizing Δ with respect to $\mathbf{r}_p$ using the method of steepest descent.

3.2 Results

Magnetic field readings and residuals versus distance between the valve moment and ring core sensing element are shown in Figure 9 for valve model #52-266 serial #2. The signal from this valve ranged up to 8,000 nT at a distance of 0.38m, from which one immediately estimates a moment magnitude of 220 nT-m^3 ($8{,}000*0.38^3/2$). The residuals in the bottom panel are on the order of 10% when assuming the valve moment is located at the valve body center and ~1% when the moment location is obtained. The actual Δs are 7.8% and 1.5% without and with the additional moment location offset, respectively. The significant reduction in residuals indicates that the moment location offset is a significant correction and was required to achieve the desired accuracy.

Table 1 shows the moment results and normalized residuals (expressed as a percentage) for all of the valves. For the V27200-818-1 valves the moments in both the 'open' and 'closed' (normal flight operations) positions are shown. There is roughly a factor of 7 difference in moment between 'open' and 'closed' for these valves. Also note that the location of the moment is about 1.5 cm different. In this case the displacement is along the axis of the tubing and the moment direction (X). The valve models #52-266 show a maximum variation in magnetic moment of nearly a factor of two, from 176 nT-m^3 to 310 nT-m^3.

The residuals are ~1.5% for valve models #52-266, ~4% for valve models #V27200-818-1 and ~5% for valve models #V110470-01. The 23% residual for valve model #V27200-818-1 serial #1 reflects that the data for this valve were obtained with the magnetometer in the same location as all of the other tests. After the runs for this valve were made and the moment analyzed, it was decided to move the test magnetometer closer to the center of the test table. The ~4% residuals for serial #s 2 and 3 for this valve model reflect the improvement in signal to noise that resulted from this change. Since the valve moments for these valves are so small, re-measuring the moment for serial #1 was not necessary.

The valve moment locations were highly consistent, within 1 mm, between valves of the same model. This consistency is in agreement with the accuracy of the position measurements, ±0.5mm. The 1 to 3 cm position corrections were therefore considered to be reliable and the average for a given valve model will be used for all valves of that model when calculating the expected field from the propulsion system.

3.3 Assessment

The MESSENGER magnetometer is separated by more than 3.6m from the propulsion system, 4.0m is a reasonable lower limit for the distance to the nearest valve since the propulsion system sub-assemblies are removed further from the magnetometer hinge attach point. The magnetic moments of the 3/8" and 1/4" latch valves, models 52-266 and V1E10470-1 are primarily in the Z direction, or normal to the valve mounting surface with a component approximately 1/6 as large parallel to the tubing axis. The high pressure valves, V27200-818-1, have their moments directed along the tubing axis and are tiny by comparison with the other valves. It turns out that the valves are all mounted with the largest component of their moment in the plane normal to the direction in which the magnetometer boom deploys. This means that the field will be roughly half as large as it otherwise could have been and a good estimate for the field from a given valve is obtained by multiplying the moment magnitude by 1/64.0 m^{-3} (rather than the more conservative value of 2/64 m^{-3}). Table 2 shows the expected field from each valve calculated using the moment magnitude of each valve together with estimates in the uncertainties in the moments. The total field of 24nT is somewhat conservative since the fields were assumed to add which would only be true if the valve moments all had the same orientation. This is actually approximately true since the two high pressure valves and one 3/8" latch valve are on one panel while all the remaining valves are on the other panel.

If the residuals are due to an unknown systematic error in our measurement technique, then they indicate an error estimate. A 3-sigma upper limit for an uncertainty due to unknown systematic errors in the measurements is evaluated simply as three times the sum of the moment errors (excluding the largest moment case of each valve model to account for flight spares) and is 81 nT-m^3 (5.3%). If the residuals reflect a random error then they are actually an estimate of the standard deviation of ΔB relative to the mean. In that case, the error in the mean would be better estimated. Considering that the residual is comprised of 72 independent measurements (taking each vector measurement as one independent data point) the error in the mean is a factor of $1/\sqrt{72} = 0.12$ smaller than the residuals. The 3-sigma uncertainties in the moments are then estimated as 0.12*3 = 0.36 times the residuals and the total uncertainty is the square root of the sum of the squared uncertainties which is 3.5 nT-m^3 (0.23%). Our absolute worst case 3-sigma error in the prediction of the contamination field is 1.3 nT (5.3%) but the error may be as low as 0.05 nT (0.23%). It is therefore almost certain that our prediction of the contamination field will be more accurate than 1 nT.

4. Figures and Tables.

Figure 1. Building 112, the JHU/APL magnetics facility building.

Figure 2. Helmholtz coils.

Figure 3. Installing valve in test fixture.

Figure 4. Six orientations of the fixture box.

Figure 5. The magnetometer was positioned on an aluminum box channel mounted to a tripod. The level of the magnetometer was adjusted to better than 0.5° and one corner of the magnetometer was chosen as the reference point.

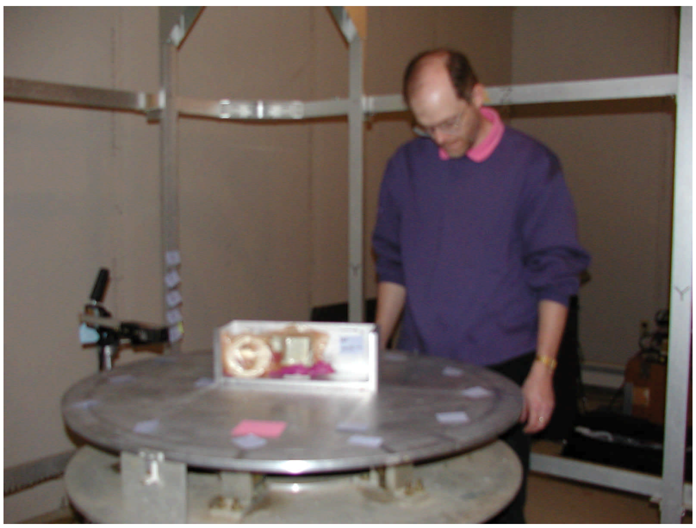

Figure 6. Rotating the table in 30° increments, waiting approximately 5 seconds at each step, constitutes one ‘run’. Measurements for a given valve consisted of six such runs.

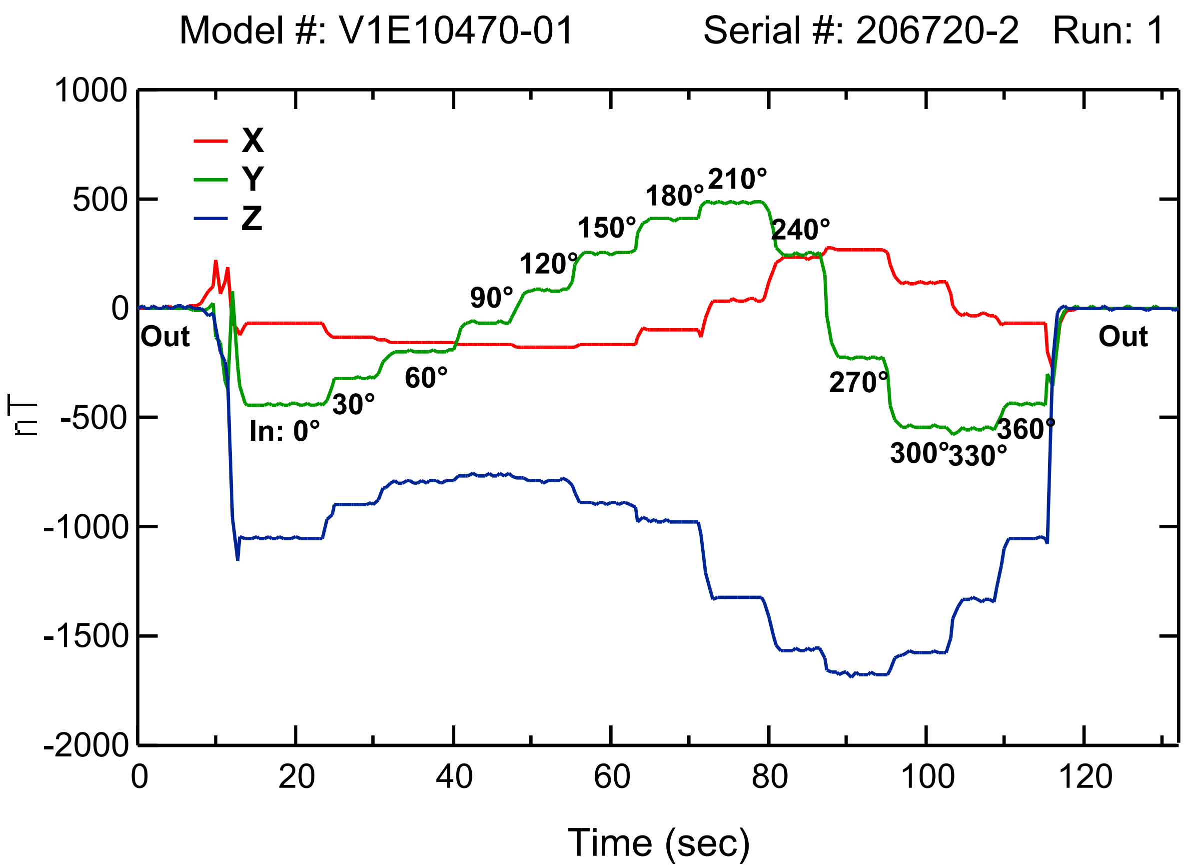

Figure 6. Magnetic field data for run 1 for valve V1E10470-01, 206720-2. In this display, the first magnetic field value is subtracted from each time series. In this case, the dominant -Z component implies that the valve moment is primarily in the +Z direction.

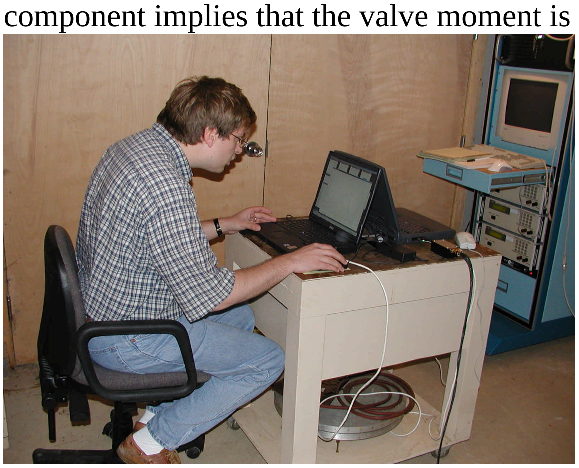

Figure 7. Magnetometer laptop networked to analysis laptop for immediate analysis of the results to assess data quality.

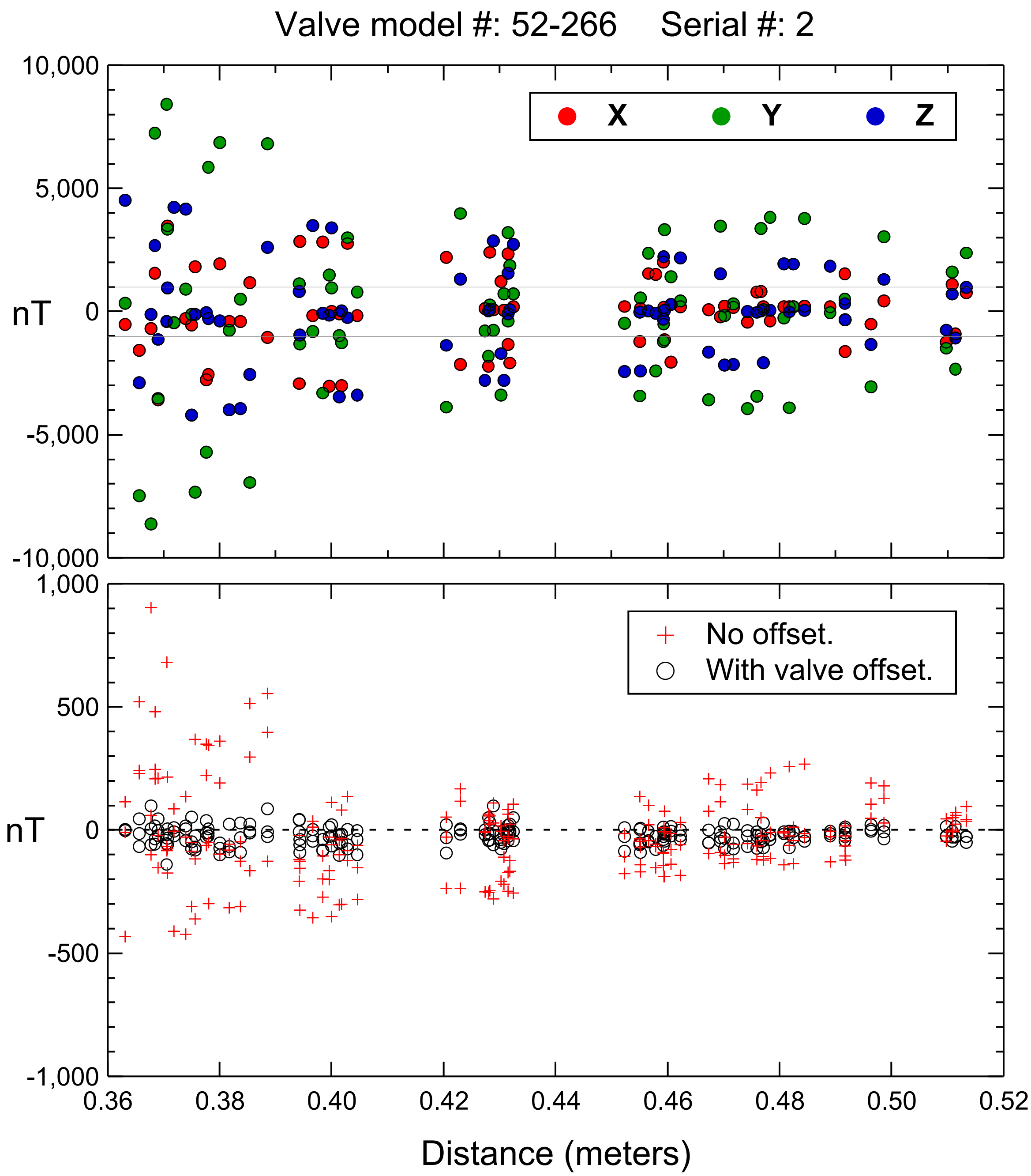

Figure 8. Magnetic field values and residuals for valved 52-266 Serial #2. Top panel shows magnetic field readings, X, Y and Z components versus distance between corresponding fluxgate ring core element and latch valve. Lines as ±1,000 nT in top panel show full scale range for bottom panel. Bottom panel shows residuals for moment solutions in which the valve moment is assumed to coincide with the valve body center, 'No offset', and for the solution in which the moment position is a free parameter, 'With valve offset'.

Model Number	Serial Number	M_X	M_Y [nT m^3]	M_Z	Residual [%]	dX	dY [cm]	dZ
52-266	1	-59.7	3.7	309.7	1.34	0.04	-0.17	-1.17
52-266	2	-30.3	4.1	217.3	1.50	-0.04	-0.10	-1.16
52-266	3	-38.4	7.3	205.7	1.56	-0.08	-0.14	-1.15
52-266	4	-45.1	9.4	271.9	1.43	-0.11	-0.17	-1.18
52-266	5	-44.3	4.0	273.3	1.42	-0.09	-0.13	-1.19
52-266	6	-46.2	4.8	272.1	1.42	-0.10	-0.13	-1.21
52-266	7	-33.3	7.3	176.1	1.58	0.08	-0.16	-1.21
V27200-818-1	1	-6.6	0.0	0.1	23.03	-1.67	-0.05	-3.29
V27200-818-1	2	-6.4	-1.6	1.9	3.72	-1.60	-0.12	-3.35
V27200-818-1	3	-7.7	0.5	1.7	3.94	-1.73	0.02	-3.24
V1E10470-01	206720-1	19.7	1.2	81.2	4.91	0.26	-0.03	-1.07
V1E10470-01	206720-2	18.1	0.5	82.0	4.32	0.28	-0.07	-1.09
*V27200-818-1	1	50.0	-0.1	0.0	3.82	-0.11	0.03	-3.66
*V27200-818-1	2	43.7	-1.4	0.6	4.26	-0.15	0.05	-3.72
*V27200-818-1	3	43.9	0.0	-1.2	4.35	-0.03	0.04	-3.70

* Valves initially measured in ‘open’ configuration. Changed to flight ‘closed’ position for measurements reported in main body of table.

Table 1. Moments and moment location offsets for MESSENGER flight valves and flight spares. Valves 52-266 and V27200-818-1 will be ‘closed’ during normal operations and were tested in the ‘closed’ position. Valves V1E10470-01 will be ‘open’ during normal operations and were tested in the ‘open’ position.

Model Number	Serial Number	Moment [nT-m3]	ΔM 3-sigma [nT-m3]	ΔB at MAG [nT]
52-266	1	315.46	1.52	4.9
52-266	2	219.43	1.18	3.4
52-266	3	209.41	1.17	3.3
52-266	4	275.79	1.42	4.3
52-266	5	276.93	1.41	4.3
52-266	6	276.03	1.41	4.3
52-266	7	179.36	1.02	2.8
V27200-818-1	1	6.62	0.55	0.1
V27200-818-1	2	6.90	0.09	0.1
V27200-818-1	3	7.96	0.11	0.1
V1E10470-01	206720-1	83.59	1.48	1.3
V1E10470-01	206720-2	84.01	1.31	1.3
System:	(smallest μ)	1534.05	3.5 (81)	24.0

Table 2. Moment magnitudes and estimated magnetic field at MESSENGER magnetometer. The net moment is calculated excluding the largest moment value of each valve model since this will be designated as the flight spare. The estimated net uncertainties are 3.5 nT-m3 (0.23%) and 81 nT-m3 (5.3%) if the residuals are attributed to random or systematic errors, respectively.