

A first comparison between ionospheric and surface level magnetic fields at Mars

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Key Points:

- Ionospheric magnetic fields are compared to surface magnetic fields at Mars for the first time
- The direction of the surface crustal field is detectable up to 250 km altitude
- Variations in the residual fields are suggestive of weak but highly variable ionospheric currents

Abstract

With both the Mars Atmosphere and Volatile Evolution (MAVEN) mission and the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission concurrently operating at Mars, we are able to make two point comparisons of the vector magnetic field at Mars for the first time. During MAVEN overflights of the InSight landing site, we compared deviations in the ionospheric magnetic field to variations in the surface level magnetic field. We find significant orbit to orbit variability in the magnitude and direction of the ionospheric magnetic field as well as significant day to day variability of the surface level magnetic field. We attribute this variability to time varying ionospheric currents. However, when analyzing the ensemble of 16 individual MAVEN overflights of the InSight landing location, we see no clear correlation between the magnitudes or directions of the ionospheric magnetic field and the surface magnetic field as might be expected. If the presumed ionospheric currents have a small scale size, then the ionospheric magnetic field will display increased variability as MAVEN flies through the current structure. Whereas the present analysis is restricted to mostly nightside MAVEN overflights where current are expected to be weak, future analyses should incorporate dayside overflights where current are expected to be stronger and current signatures more clear.

Plain Language Summary

Two mission currently operating at Mars have instruments that measure magnetic fields: the Mars Atmosphere and Volatile Evolution (MAVEN) mission which has been orbiting Mars since September 2014 and the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission which landed on the surface of Mars in November 2018. This allows us to make two point comparisons of the magnetic field at Mars for the first time. We compare the magnetic field in the upper atmosphere below 250 km altitude measured by MAVEN to the magnetic field at the surface measured by InSight during times when MAVEN is directly above InSight. The magnetic field measured by MAVEN shows considerable variability from orbit to orbit over the same location. At the same time, the surface magnetic field measured by InSight shows considerable day to day variations. We suggest that this variability is caused by electric currents flowing in the upper atmosphere of Mars in the vicinity of MAVEN.

1 Introduction

For well over a century, surface level magnetic field measurements have been used to study atmospheric, ionospheric, and magnetospheric dynamics at Earth (e.g., Schuster, 1889; Birkeland, 1908). Spatial and temporal changes in current systems and magnetic field configurations can be inferred remotely from changes in the magnetic fields they produce. With the landing of InSight on Mars in the near equatorial Elysium Planitia on 26 November 2018, the InSight FluxGate magnetometer (IFG) now provides the first surface level magnetic field measurements on another planet (Banfield et al., 2018). Already, time variations in the measured magnetic field have been interpreted as resulting from atmospheric/ionospheric and magnetospheric processes (Johnson et al., 2020; Mittelholz et al., 2020).

Additionally, the Mars Atmosphere and Volatile Evolution Mission, MAVEN, has been orbiting Mars since September 2014 (Jakosky et al., 2015). MAVEN carries a suite of plasma instruments, including the only currently operating magnetometer in orbit (Connerney et al. 2015), in order to characterize the upper atmosphere and space environment around Mars

including the solar wind, magnetosheath, magnetotail, and ionosphere. Its elliptical orbit typically brings MAVEN to within ~ 150 km of the surface, directly sampling the neutral and plasma constituents (Mahaffy et al., 2014, McFadden et al., 2015) as well as the ambient magnetic field (Connerney et al., 2015) in the upper atmosphere.

Thus, starting with InSight operations in late 2018, two-point vector magnetic field measurements are possible at Mars for the first time. We are able to compare changes in the magnetic field in the ionosphere to changes in the surface magnetic field in order to determine the sources of the variability in the surface magnetic field. Here, we focus on intervals when MAVEN was in the ionosphere directly overhead InSight.

Magnetic field perturbations due to changing ionospheric currents can be measured on the ground. Recently, Lillis et al. (2019) computed the expected magnetic field perturbations due to neutral wind driven currents in the ionosphere. They predicted surface level magnetic field variations of a few tens of nT. Johnson et al. (2020) interpreted the repeatable diurnal variation in the surface level magnetic field measured by IFG as a result of ionospheric currents. Additionally, Mittelholz et al. (2020), by looking at over one Earth year of IFG data, reported evidence of seasonal changes in the diurnal magnetic field signal consistent with seasonal changes in the modeled thermospheric winds which drive ionospheric currents.

Here, we compare in-situ MAVEN magnetic field measurements in the ionosphere above InSight to IFG surface level magnetic field measurements in an attempt to correlate changes in the surface magnetic field to ionospheric dynamics. In the next section, we summarize the data and data selection criteria. In Section 3, we compare MAVEN and IFG data from different individual MAVEN overflights at the same local time and statistically compare the variations in the surface magnetic field to deviations in the ionosphere magnetic field. Finally we discuss the result and future directions.

2 Data and Data Selection

On 26 November 2018 InSight landed on Mars at 4.50° N, 135.63° E in Elysium Planitia (Banerdt et al., 2020). As part of the Auxiliary Payload Sensor Suite (APSS), InSight carries a fluxgate magnetometer with the primary purpose of measuring the magnetic field environment to characterize and remove this from the seismic data (Banfield et al., 2018). The sampling rate of the IFG is 20 Hz which is decimated to 0.2 Hz or 2 Hz depending upon telemetry constraints. Limited 20 Hz data can additionally be downlinked on request from the science team [Johnson et al., 2020]. In this study we use the decimated data (either 0.2 or 2 Hz) in the Lander Level Frame in which X is North, Y is East and, Z is vertically Down (i.e., NED coordinates) [Joy et al., 2019].

The MAVEN magnetometer (MAG) (Connerney et al., 2015) has been observing the magnetic environment around Mars since orbit insertion in September 2014. The intrinsic sampling rate is 32 Hz. In this study we use the 1-second averaged data products as provided on the Planetary Data System (PDS).

It is well known that some regions of the martian crust are magnetized resulting in crustal magnetic fields (Acuna et al., 2001). InSight is in a region of moderate magnetization between the weakly magnetized northern hemisphere and the more strongly magnetized southern hemisphere (Mittelholz et al., 2018; Johnson et al., 2020). In order to determine the magnetic field variations due to ionospheric electric currents, we must remove the crustal contribution

from the MAVEN-measured magnetic field. For this, we use the recent global magnetic field model of Langlais et al. (2019) (hereafter referred to as L19). This is the first global model to incorporate lower altitude MAVEN data down to 150 km. The spatial resolution of the model is ~ 160 km which corresponds to a spherical harmonic model degree of 134.

During January/February 2019, July/August 2019, and December 2019/January 2020, MAVEN's periapsis (at ~ 150 km altitude) was above the InSight landing site. Here we focus on the first two of these time intervals, January/February 2019 and July/August 2019, as both MAVEN and IFG data are available from the PDS for these intervals. As of this writing, the data covering the complete third interval were not available. For our analysis, we selected intervals when MAVEN was within $\pm 4^\circ$ latitude and longitude of InSight and at altitudes less than 250 km. Figure 1 graphically shows the MAVEN orbit during these intervals and the location of InSight in local time during the MAVEN overflights.

Table 1 lists the time intervals when these criteria were satisfied as well as the mean local

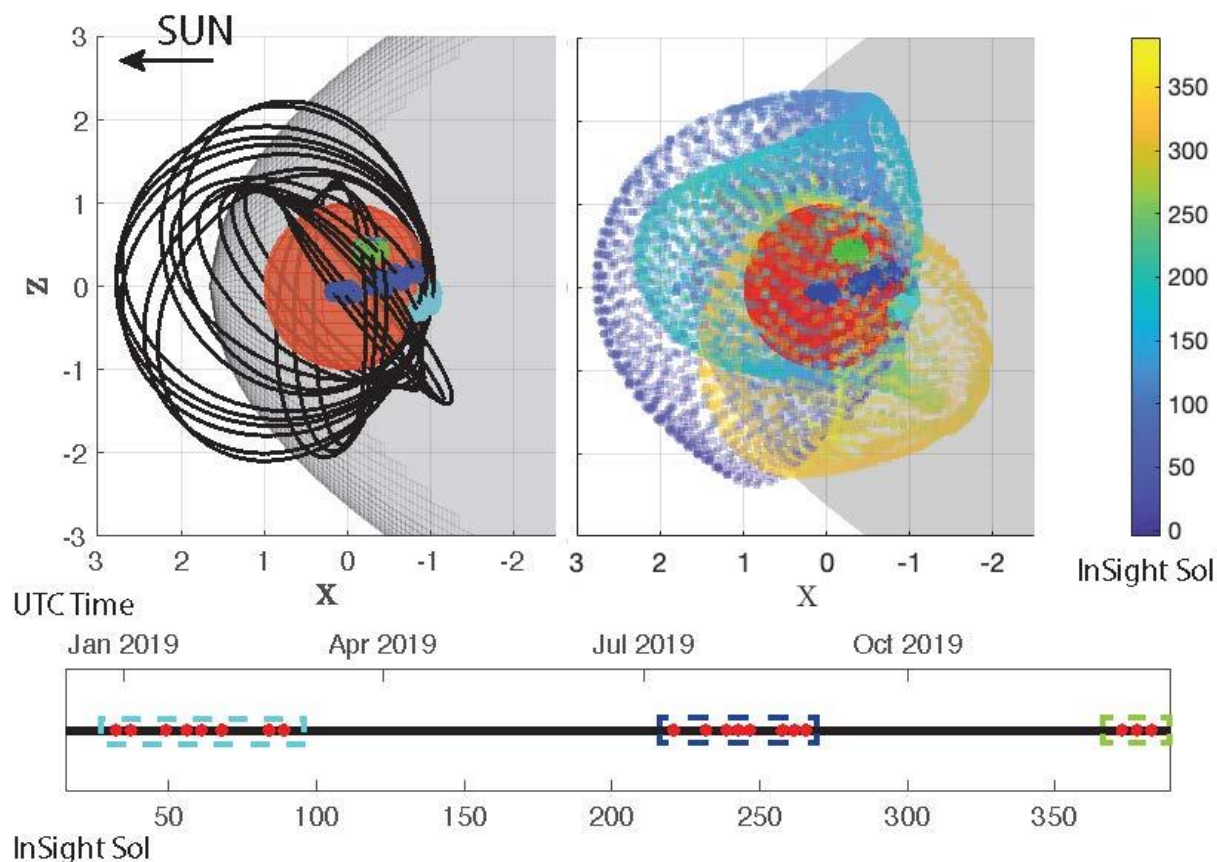


Figure 1: An overview of MAVEN coverage for InSight sols 1-389. The left panel only shows orbits that passed within a 4 degree circle of InSight Landing Site and below 250 km. The track sections discussed in this paper are highlighted in color according to sampling time in January/February (cyan), July/August (blue) and December (green) (January 2020 data were not yet publicly available). The right panels show every 5000th MAVEN data point (from the 1 Hz data) for every orbit during this time frame color coded according to InSight sol. The grey area represents a model bow shock (Vignes et al., 2000). The bottom timeline highlights areas at which overflights occurred using the same coloring scheme as above.

solar time at the InSight landing site. Of the twenty MAVEN overflight intervals, a total of sixteen intervals of coincident MAVEN and IFG data were analyzed. As noted in Table 1, no IFG data were available for three MAVEN overflights; these data gaps were due to Payload Auxiliary Electronics (PAE) anomalies on the InSight lander. A further interval (on 15 July 2019) was excluded from analysis due to the short duration of the overflight (< 10 seconds) because the MAVEN trajectory just skimmed the edge of the $\pm 4^\circ$ region around InSight. Most overflights last one to two minutes as MAVEN traverses a larger span of the region (up to ~ 500 km) traveling at speed of a few km per second.

Start time (UT)	End time (UT)	MLST
2018-12-29/05:09:20	2018-12-29/05:10:00	no IFG data
2019-01-03/08:20:00	2019-01-03/08:21:20	01:51
2019-01-10/11:55:40	2019-01-10/11:56:30	00:50
2019-01-15/15:09:50	2019-01-15/15:11:40	00:47
2019-01-22/18:52:20	2019-01-22/18:53:20	23:52
2019-01-27/22:10:10	2019-01-27/22:12:00	23:53
2019-02-04/01:53:50	2019-02-04/01:55:40	23:02
2019-02-09/05:16:40	2019-02-09/05:17:00	23:06
2019-02-20/11:18:10	2019-02-20/11:20:10	21:56
2019-02-25/14:17:50	2019-02-25/14:19:50	21:40
2019-07-11/04:42:00	2019-07-11/04:43:40	21:42
2019-07-15/07:21:20	2019-07-15/07:21:20	duration < 10 sec
2019-07-18/08:22:20	2019-07-18/08:22:30	20:48
2019-07-22/10:58:50	2019-07-22/11:00:40	no IFG data
2019-07-29/14:35:50	2019-07-29/14:36:30	19:52
2019-08-02/17:10:10	2019-08-02/17:12:00	19:49
2019-08-06/19:39:40	2019-08-06/19:40:30	no IFG data
2019-08-18/01:18:50	2019-08-18/01:20:30	18:11
2019-08-22/03:38:40	2019-08-22/03:40:20	17:53
2019-08-26/05:57:50	2019-08-26/05:58:10	17:35

Table 1: Start and end times of MAVEN overflights for the periods highlighted in cyan and blue in Figure 1. The third column lists the Mean Local Solar Time at the InSight landing site whenever IFG data is available. No IFG data was collected during Payload Auxiliary Electronics anomalies.

As can be seen in Figure 1 and Table 1, most of the overflights occurred during nighttime, in the dusk and midnight local time sectors, due to the orbit geometry of MAVEN. As mentioned below, this fact complicates the interpretation since ionospheric current densities are expected to be much lower at night due to the smaller plasma density.

141 **3 Results**

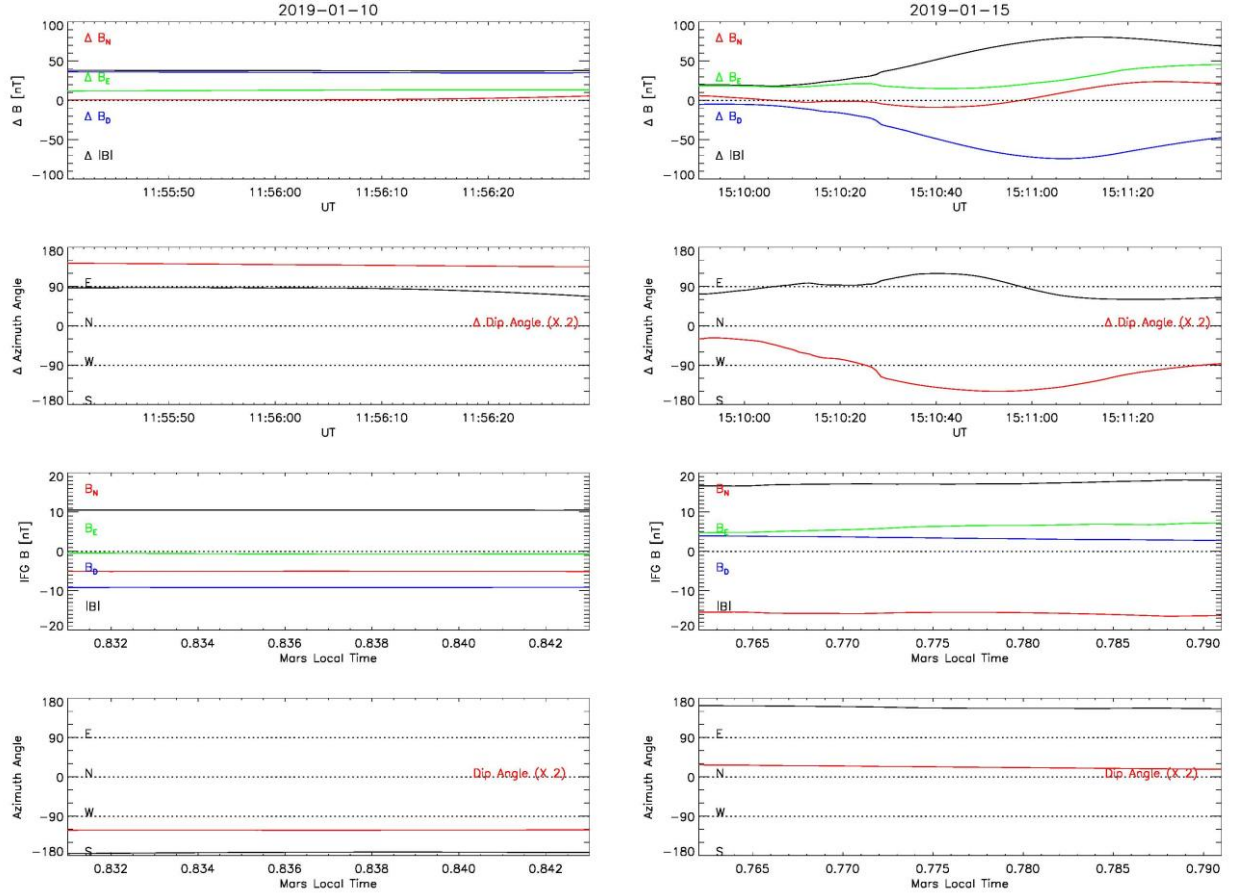


Figure 2: Examples of magnetic field data on two orbits from the 10 January 2019, InSight sol 44 (left) and 15 January 2019, sol 49 (right) overflights of InSight by MAVEN. In each column, the top panel shows the residual ionospheric magnetic field in North, East, Down components (in red, green, blue, respectively) as well as the magnitude of the residual magnetic field. The second panel shows the azimuth angle (black) and dip angle (multiplied by a factor of 2, red) of residual ionospheric magnetic field. The third panel shows the residual surface magnetic field in the same coordinate system as the top panel. The bottom panel shows the corresponding azimuth and dip angles for the residual surface magnetic field. The ionospheric data are plotted against Universal Time while the surface data are plotted against Mars Mean Solar Local Time.

Figures 2 and 3 show examples of ionospheric magnetic field data from MAVEN and surface magnetic field data from IFG for two different overflights that occurred at approximately the same local time. Figure 2 compares data from 10 January 2019 (InSight sol 44) and 15 January 2019 (sol 49) collected just past midnight Mars local time ($\sim 00:50$ local time). Figure 3 compares data from 29 July 2019 (sol 238) and 2 August 2019 (sol 242). In all cases, the top panel shows the residual ionospheric magnetic field - i.e., the ionospheric magnetic field measured by MAVEN with the L19 magnetic field model subtracted - in NED coordinates. The second panel shows the azimuth and dip angles of the residual ionospheric field. The azimuth angle is measured clockwise from north, and the dip (or inclination) angle is measured positive downward from horizontal. In the second (and fourth panels), the dip angle is multiplied by a factor of 2 for clarity. The third panel shows the residual surface magnetic field measured by IFG in NED coordinates. The median of each component was computed for each 60-day overflight

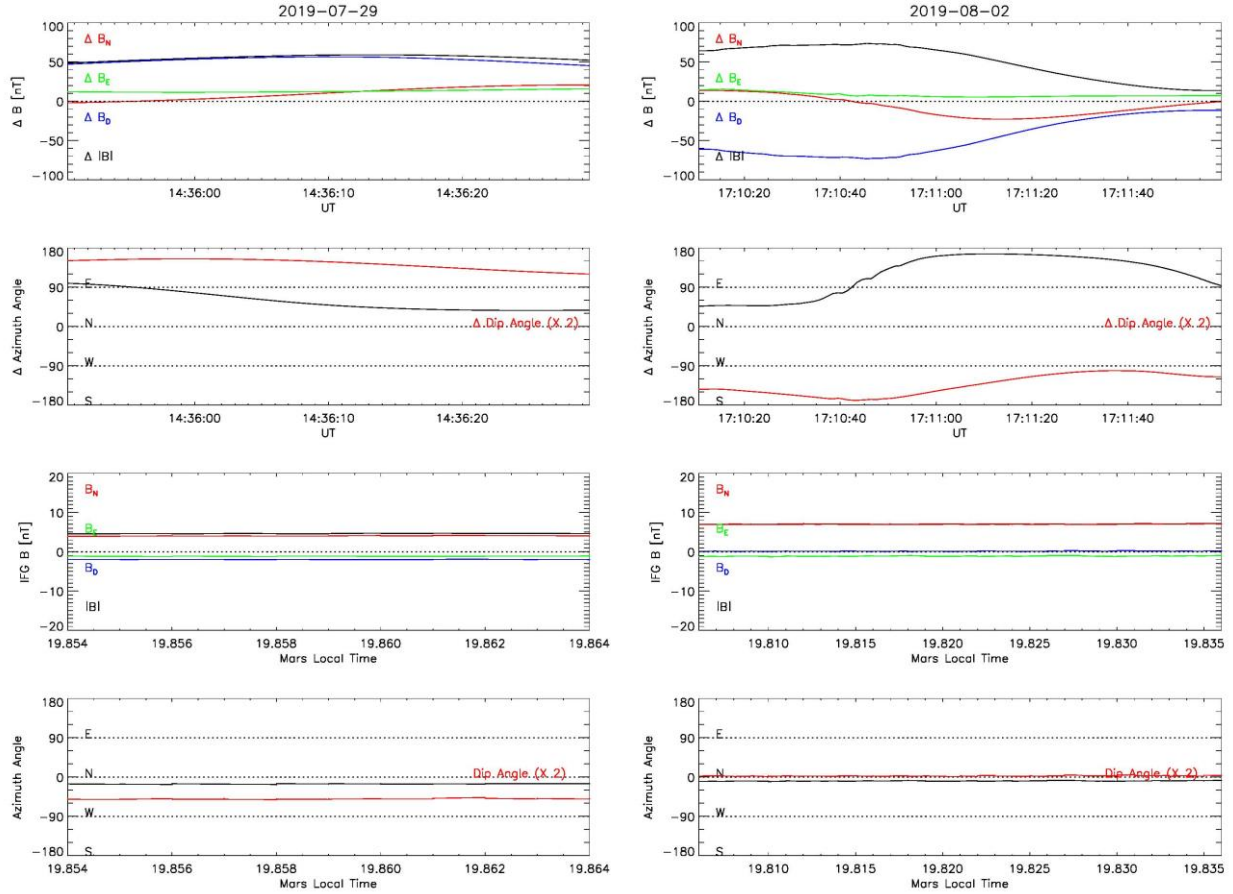


Figure 3: Same as Figure 2 except for 29 July 2019, sol 238 (left) and 2 August 2019, sol 242 (right).

interval (January/February 2019 and July/August 2019 separately) and subtracted from the IFG measured surface field. Finally, the fourth panel shows the azimuth and dip angles of the residual surface magnetic field.

It can be seen in both Figures that even though MAVEN is passing over the same region Mars, the residual ionospheric magnetic field varies from orbit to orbit. For example, on 10 January 2019, the residual magnetic field is small (< 15 nT) and relatively stable in direction. Five days later, when MAVEN traverses nearly the same trajectory, there are significant variations in the residual ionospheric magnetic field, particularly in the vertical (D) component; the azimuthal component rotates by nearly 90° and the dip angle changes sign. Likewise, there are day to day differences in the surface magnetic field even at the same local time. From 10 January to 15 January 2019, the magnitude of the residual surface magnetic field also increases by nearly 10 nT, and the dip angle changes from negative to positive (upward pointing to downward pointing). Similar, though not quite as extreme variations are seen when comparing 29 July and 2 August 2019 in Figure 3.

Even though the possibility of small scale magnetic fields of crustal origin that are not captured by the model cannot be completely ruled out, we interpret this orbit to orbit variability in the ionospheric field as resulting from variability in small scale ionospheric current structures. The steep slope in the residual magnetic field near 15:10:27 UT on 15 January 2019, particularly in the vertical component and the dip angle, is consistent with the magnetic signature of a thin

current layer. Similarly, the more gradual change in sign of the vertical component and dip angle would be consistent with a broader current. From a single observation platform, it is impossible to uniquely determine the geometry of a current system that would produce similar magnetic deflections, so we refrain from speculating too much about the direction of such a current system.

Changes in the residual surface field magnitude and direction would also result from time-varying ionospheric currents. From 10 January to 15 January, the vertical component of the residual surface field changes from negative to slightly positive (upward pointing to nearly horizontal) and the north component increases in magnitude (becomes more southward) by ~ 10 nT. Assuming the current is above InSight (a reasonable assumption in this case), this would be consistent with the appearance or intensification of a westward current in the ionosphere above the lander. However, again, we caution that it is ill-advised to try to extrapolate too much about the current configurations given limited observation points.

For a more statistical view, Figure 4 compares the ionospheric magnetic field to the residual surface magnetic field for all 16 intervals. The first column shows a scatter plot of the magnitude of the total ionospheric magnetic field as measured by MAVEN when it is over InSight and the magnitude of the residual surface magnetic field from IFG. The second column shows the azimuth angle of the ionospheric magnetic field versus the azimuth angle of the residual surface magnetic field. The third column plots the dip angle of the ionospheric field versus the dip angle of the surface magnetic field. The bottom row plots the same quantities except the vertical axes represent the residual ionospheric field: the observed magnetic field minus the model crustal magnetic field of L19 (i.e., the same data as shown in Figures 2 and 3). The color in all panels corresponds to altitude. Brown shades represent ionospheric data below 200 km while blue shades represent data above 200 km. The tint increases (becomes whiter) near 200 km and the shade increases (becomes darker) toward the extremes of 150 km and 250 km. Since the MAVEN data typically vary more than the IFG data during each individual, the vertical stripes on the plots can be interpreted as individual overflights of MAVEN.

Several things are immediately noticeable from this comparison. In general, the magnitude of the ionosphere magnetic field is slightly larger at lower altitudes (top row, left panel). This is expected since InSight is located in a region of moderate crustal magnetic field. The azimuth angle of the total ionospheric magnetic field is generally in the south-east direction, between 90 and 180 degrees (top row, middle panel). This is in general agreement with the direction of the total (not residual) surface magnetic field. As reported in Johnson et al. (2020), the azimuth angle of the average total surface magnetic field is 139° suggesting that the influence of the surface magnetic field reaches to at least 250 km altitude. The dip angle of the ionospheric magnetic field does not appear to have any correlation with altitude or the surface magnetic field. The dip angle of the average total surface field is -27° (Johnson et al., 2020). The ionospheric magnetic field dip angle varies substantially at all altitudes.

From the top row of Figure 4, it is clear that there is substantial variation in the magnitude, azimuth angle and dip angle of the residual surface magnetic field. However, there does not appear to be any clear correlation between the total ionospheric magnetic field and the residual surface magnetic field.

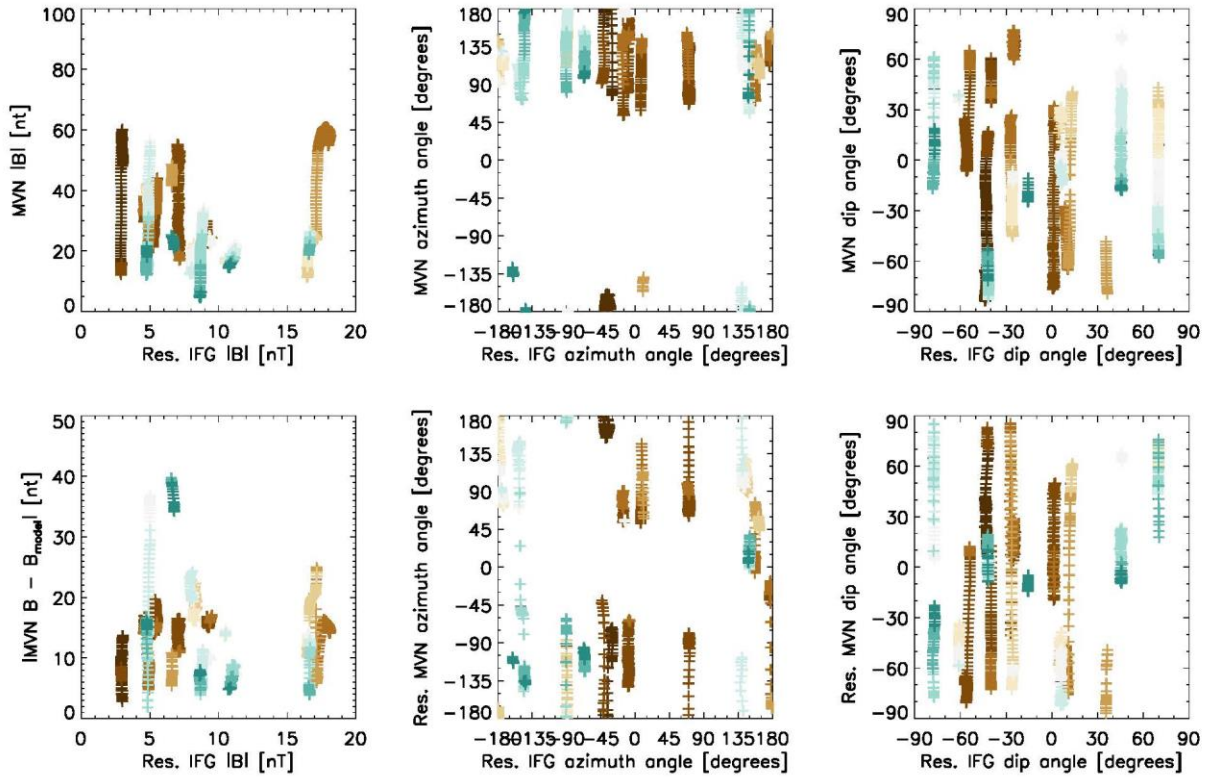


Figure 4: Top row, left to right: total ionospheric magnetic field strength, $|B|$, as measured by MAVEN above InSight versus the magnitude of the residual (demeaned) surface magnetic field from IFG, ionospheric magnetic field azimuthal angle versus the surface magnetic field azimuthal angle, ionospheric magnetic field dip angle versus the surface magnetic field dip angle. Bottom row: same quantities except with the crustal magnetic field prediction of Langlais et al. (2019) removed from the ionospheric magnetic field. Colors represent altitude. Brown colors correspond to ionospheric altitudes below 200 km, and blue colors correspond to altitudes above 200 km.

The magnitude of the residual ionospheric magnetic field (bottom row, left panel) is generally much lower than the magnitude of the total ionospheric magnetic field (note the change in the vertical axis between the top left and bottom left panels in Figure 4), suggesting that the crustal magnetic field model of L19 does take into account a significant part of the crustal magnetic field contribution. Additionally, the largest residual ionosphere magnetic fields occur at the highest altitudes analyzed. In fact, residual ionospheric magnetic field magnitudes greater than 25 nT only occur at altitudes higher than 200 km. We should note that the largest residual ionospheric magnetic fields also occur at the earliest local times – those MAVEN overflights at or just before dusk when the ionosphere is still sunlit. However, there does not appear to be a correlation between the magnitude of the residual ionospheric magnetic field and the magnitude of the residual surface field. When only considering the lowest altitude ionospheric data (dark brown points), there may be a weak correlation between the magnitude of the residual ionospheric magnetic field and the magnitude of the residual surface magnetic field, but there are too few data points to make a clear determination.

If the variations in the surface magnetic field are presumed to be due to ionospheric currents, one may expect a relationship between the azimuth angle of the residual ionospheric magnetic field and the azimuth angle of the residual surface magnetic field. If, for example, ionospheric currents with peak current densities near 150 km (Fillingim et al., 2012; Lillis et al., 2019) cause a deviation in the azimuth angle at the surface, one would expect the deviation in the azimuth angle in the ionospheric magnetic field above the current to be different from the surface deviation by 180° . A westward current would cause a southward deviation in the surface magnetic field and a northward deviation in the ionospheric magnetic field above the current. No such relationship is seen in Figure 4 (bottom row, middle panel); the azimuth angles of the residual ionospheric magnetic field and the surface magnetic field appear uncorrelated.

Additionally, there does not appear to be a clear correlation between the residual ionospheric magnetic field dip angle and the residual surface dip angle (bottom row, right panel). In general, for a given residual dip angle in the surface field, there is an extremely broad range of residual dip angles in the ionosphere - in some cases spanning nearly 180 degrees. This lack of correlation may in part be explained by MAVEN traveling through small scale ionospheric current structures where the residual magnetic field direction may vary significantly over several degrees of latitude (such as seen in the right columns of Figures 2 and 3).

4 Conclusions

With MAVEN and InSight data, we are able to make two-point vector magnetic field comparisons in the ionosphere and on the surface of Mars for the first time. These comparisons can reveal the sources of magnetic field variability on the surface of Mars, and at the same time may lead to new insights into atmospheric, ionospheric, and magnetospheric dynamics.

From analyzing individual MAVEN overflights of the InSight landing site, we note significant orbit to orbit variation in the ionospheric magnetic field coincident with day to day variations in the surface magnetic field even at nearly identical local times. One interpretation is that time varying ionospheric currents, which would cause orbit to orbit variations in the ionospheric magnetic field, may be the cause of day to day magnetic field variations on the surface.

Ionospheric current variability can be driven by internal (neutral winds) or external (solar wind and interplanetary magnetic field) sources. Recent measurements of thermospheric neutral winds by MAVEN have shown that neutral winds can exhibit significant orbit to orbit variations as well as substantial deviation from global circulation model predictions (Roeten et al., 2019). Additionally, changing interplanetary magnetic field conditions can affect the magnetic field at ionospheric altitudes, even on the nightside (e.g., Brain et al., 2003), which can in turn impact the strength and direction of ionospheric currents.

The lack of correlation between ionospheric and surface magnetic field deviations may argue against ionospheric currents as being the source of the orbit to orbit and day to day variations in the magnetic field deviations. However, small scale currents ($\ll 100$ km), which will produce a given magnetic field signature at a fixed location on the surface, may be observed as a relatively broad range of magnetic field magnitudes and directions as a spacecraft traverses the current producing region. We could attempt to restrict ionospheric data to within say $\pm 1^\circ$ ($\pm \sim 60$ km) of the InSight location to remove some degree of variability caused by spacecraft

motion; however, the number of overflights would decrease to a statistically insignificant number.

Another complicating factor in the above analysis and interpretation is that the available data thus far is primarily on the nightside. Nighttime ionosphere currents are expected to be weak due to the low plasma density (e.g., Lillis et al., 2019). Weak currents will produce smaller magnetic field deviations at the surface. Stronger ionospheric currents on the dayside may provide a more clear signal in the surface and ionospheric magnetic field deflections. As MAVEN's orbit continues to precess in the InSight era, future overflight opportunities (which occur with an approximate cadence of six months) will occur on the dayside.

Acknowledgments, Samples, and Data

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References

- Acuña, M. H., J. E. P. Connerney, P. Wasilewski, R. P. Lin, D. Mitchell, K. A. Anderson, et al. (2001), Magnetic field of Mars: Summary of results from the aerobraking and mapping orbits, *J. Geophys. Res.*, 106(E10), 23403-23417, doi:10.1029/2000JE001404.
- Banfield, D., J. A. Rodriguez-Manfredi, C. T. Russell, K. M. Rowe, D. Leneman, H. R. Lai, et al. (2018), InSight Auxiliary Payload Sensor Suite (APSS), *Space Sci. Rev.*, 215, 4, doi:10.1007/s11214-018-0570-x.
- Banerdt, W. B., S. E. Smrekar, D. Banfield, D. Giardini, M. Golombek, C. L. Johnson, et al. (2020), Initial results from the InSight mission on Mars, *Nat. Geosci.*, 13, 183-189, doi:10.1038.s41561-020-0544-y.
- Birkeland, K. (1908), *The Norwegian Aurora Polaris Expedition 1902-1903*, Vol. 1, H. Aschehoug & Co., Christiania (Oslo) (<https://archive.org/details/norwegianaurorap01chririch>).
- Brain, D. A., Bagenal, F., Acuña, M. H., and Connerney, J. E. P. (2003), Martian magnetic morphology: Contributions from the solar wind and crust, *J. Geophys. Res.*, 108(A12), 1424, doi:10.1029/2002JA009482.
- Connerney, J. E. P., Espley, J., Lawton, P., Murphy, S., Odom, J., Oliverson, R., & Sheppard, D. (2015), The MAVEN Magnetic Field Investigation, *Space Sci. Rev.*, 195, 257-291, doi:10.1007/s11214-015-0169-4.

- 310 Fillingim, M. O., Lillis, R. J., England, S. L., Peticolas, L. M., Brain, D. A., Halekas, J. S., et al.
 311 (2012), On wind-driven electrojets at magnetic cusps in the nightside ionosphere of Mars,
 312 *Earth Planet Space*, 64, 5, doi:10.5047/eps.2011.04.010.
- 313 Jakosky, B. M., Grebowsky, J. M., Luhmann, J. G., & Brain, D. A. (2015), Initial results from
 314 the MAVEN mission to Mars, *Geophys. Res. Lett.*, 42, 8791–8802,
 315 doi:10.1002/2015GL065271.
- 316 Johnson, C. L., Mittelholz, A., Langlais, B., Russell, C. T., Ansan, V., Banfield, D., et al. (2020),
 317 Crustal and time-varying magnetic fields at the InSight landing site on Mars, *Nat.*
 318 *Geosci.*, 13, 199–204, doi:10.1038/s41561-020-0537-x.
- 319 Joy, S. P., Mafi, J. N., & Slavney, S. (2019), Interior Exploration Using Seismic Investigations,
 320 Geodesy, and Heat Transport (InSight) Mission Insight Fluxgate Magnetometer (IFG)
 321 PDS Archive Software Interface Specification, *urn:nasa:pds:insight-ifg-*
 322 *mars:document:insight-ifg-sis*.
- 323 Langlais, B., Thébaud, E., Houliez, A., Purucker, M. E., & Lillis, R. J. (2019), A new model of
 324 the crustal magnetic field of Mars using MGS and MAVEN, *J. Geophys. Res. Planets*,
 325 124, 1542–1569, doi:10.1029/2018JE005854.
- 326 Lillis, R. J., Fillingim, M. O., Ma, Y., Gonzalez-Galindo, F., Forget, F., Johnson, C. L., et al.
 327 (2019), Modeling wind-driven ionospheric dynamo currents at Mars: Expectations for
 328 InSight magnetic field measurements, *Geophys. Res. Lett.*, 46, 5083– 5091,
 329 doi:10.1029/2019GL082536.
- 330 Mahaffy, P. R., Benna, M., King, T., Harpold, D. N., Arvey, R., Barciniak, M., et al. (2014), The
 331 Neutral Gas and Ion Mass Spectrometer on the Mars Atmosphere and Volatile Evolution
 332 Mission, *Space Sci. Rev.*, 195, 49–73, doi:10.1007/s11214-014-0091-1.
- 333 McFadden, J. P., Kortmann, O., Curtis, D., Dalton, G., Johnson, G., Abiad, R., et al. (2015),
 334 MAVEN SupraThermal and Thermal Ion Composition (STATIC) Instrument, *Space Sci.*
 335 *Rev.*, 195, 199–256, doi:10.1007/s11214-015-0175-6.
- 336 Mittelholz, A., Johnson, C. L., & Morschhauser, A. (2018), A new magnetic field activity proxy
 337 for Mars from MAVEN data, *Geophys. Res. Lett.*, 45, 5899– 5907,
 338 doi:10.1029/2018GL078425.
- 339 Mittelholz, A., Johnson, C. L., Thorne, S. N., Joy, S., Barrett, E., Clinton, J., et al. (2020), The
 340 origin of observed magnetic variability for a sol on Mars from InSight, *J. Geophys. Res.*
 341 *Planets*, submitted. (*I know papers submitted or in press are not allowed, but this
 342 manuscript was submitted as part of the same special collection*)
- 343 Roeten, K. J., Bougher, S. W., Benna, M., Mahaffy, P. R., Lee, Y., Pawlowski, D., et al. (2019),
 344 MAVEN/NGIMS thermospheric neutral wind observations: Interpretation using the M-
 345 GITM general circulation model, *J. Geophys. Res. Planets*, 124, 3283– 3303,
 346 doi:10.1029/2019JE005957.
- 347 Schuster, A. (1889), The diurnal variation of terrestrial magnetism, *Philos. Trans. R. Soc. A*, 180,
 348 467–518, doi:10.1098.rsta.1889.0015.
- 349 Vignes, D., Mazelle, C., Rème, H., Acuña, M. H., Connerney, J. E. P., Lin, R. P., et al. (2000),
 350 The solar wind interaction with Mars: Locations and shapes of the bow shock and the

351 magnetic pile-up boundary from the observations of the MAG/ER Experiment onboard
352 Mars Global Surveyor, *Geophys. Res. Lett.*, 27, 49-52, doi:10.1029/1999GL010703.