Mysterious misalignments between geomagnetic and stellar reference frames seen in CHAMP and Swarm satellite measurements

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The orientation of a spacecraft in Low Earth Orbit can be determined accurately from either magnetic field measurements or star camera images. Ideally, the independently computed spacecraft attitudes should agree. However, we find that the German CHAMP and European Space Agency triple-satellite Swarm geomagnetic satellites exhibit consistent misalignments between the stellar and geomagnetic reference frames, which oscillate with the local time of the orbit. Having an amplitude of 20 arc seconds, these oscillations are more than an order of magnitude larger than the stability of the optical bench, which co-hosts the magnetometers and star cameras. The misalignments could originate either from the magnetometer or star camera measurements. On one hand, as-yet-unknown external magnetic field contributions could appear as a rotation of the geomagnetic reference frame. On the other hand, the observed misalignments agree in amplitude and phase with the effects of stellar aberration, caused by the movement of the star cameras relative to the light rays emitted by the stars. This is surprising because stellar aberration is allegedly already corrected for by the star image processing system. Resolving these mysterious misalignments is key to fulfilling the measurement accuracy requirements and science objectives of the ongoing Swarm mission. If caused by stellar aberration, fully correcting for this effect could significantly improve the attitude accuracy not only of CHAMP and Swarm, but also of several other past and ongoing scientific satellite missions.

Keywords: Satellite geomagnetism, stellar compass, stellar aberration

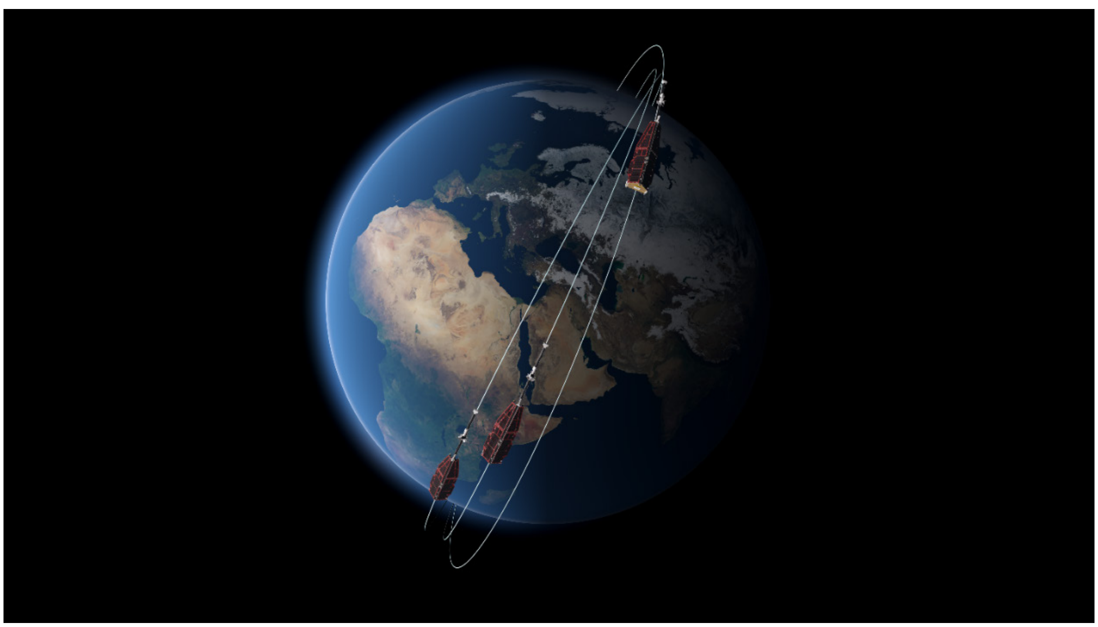

Figure 1: The 3 satellites of the Swarm constellation are currently still all in very similar orbits, which will drift apart over the course of the mission. Image courtesy European Space Agency.

Geomagnetic satellite missions carry a vector magnetometer co-located with a multi-head star tracker on an optical bench. The CHAMP mission (Reigber et al., 2002) has dual-head cameras (Maurizio et al., 2004), while the 3 satellites (Figure 1) of the Swarm constellation (Friis-Christenson et al., 2009) employ a triple-head camera system. After correcting for a constant misalignment between the magnetometer and star camera instrument frames, the attitude determined from the star camera should agree with the attitude inferred from the magnetometer to within about 2 arc seconds (Haagmans, 2005) to fulfill the mission requirements. What is seen instead is a regularly oscillating misalignment with about 20 arc seconds amplitude.

Let us define a right-handed spacecraft coordinate system with X to the front, Y horizontally to the right and Z vertically down. Then we can describe misalignments between the geomagnetic and the stellar reference frames by rotations alpha, beta and gamma about the X, Y and Z axes. The plots in Figure 2 show how much the stellar reference system would have to be rotated clockwise about each axis in order to align it with the geomagnetic reference frame. Since the geomagnetic field is quite variable, the geomagnetic reference frame can only be determined with high accuracy when a large number of measurements are averaged. Here, the misalignment was determined by computing the residuals from magnetic measurements in the range of -30° to 30° geomagnetic apex latitude (Richmond, 1995) for night-side hemisphere over a period of 3 days and minimizing them against the latest 9th revision of the scientific geomagnetic field model POMME (Maus et al., 2010). Subsequent inversions were then averaged using a running window of 90 days. This leads to smooth curves for the misalignment angles, which are plotted in Figure 2 for CHAMP and the three Swarm spacecraft.

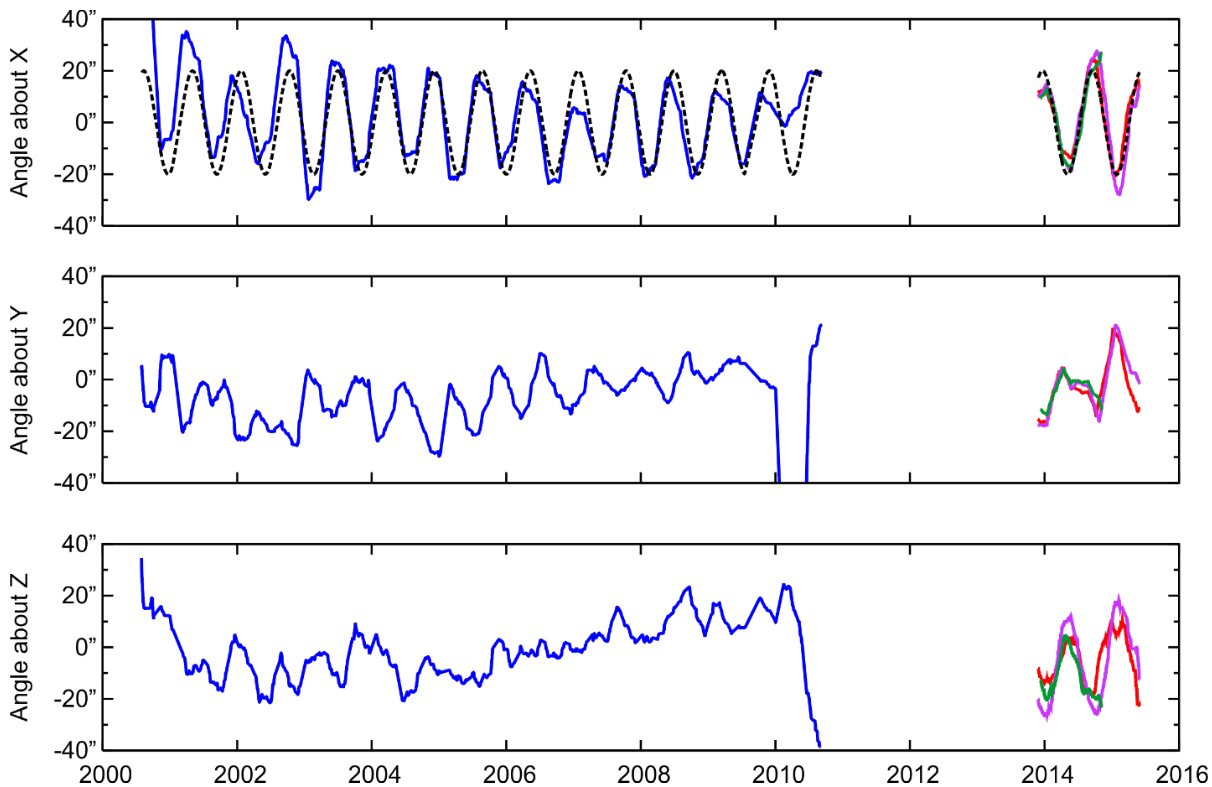

Figure 2: Mis-alignment angle variations over time for the CHAMP mission (blue) and the 3 Swarm satellites (red, purple and green). The dashed black curve in the top panel shows the approximate effect of stellar aberration on the alpha angle, if it had not been corrected for. In the beta (Y) and gamma (Z) angles the stellar aberation effect is not easily predictible, since it depends

on which camera heads are combined for the attitude solution.The aberration effect in beta and gamma would also be different for CHAMP and Swarm, due to different camera head configurations, while it is identical in alpha.

This technique of estimating misalignment angles had been employed regularly by the author for the CHAMP mission to calibrate the misalignment angles. The oscillation in the alpha angle rotation about the X axis was soon noticed but remained mysterious throughout the mission. Since the oscillations correlate with local time, and thus with different spacecraft temperatures and illuminations of the optical bench, it was thought to be due to thermal instabilities between the star cameras and the vector magnetometer. This theory is no longer tenable since the launch of the three identical Swarm spacecraft in November 2013, which have highly stable optical benches, but all exhibit precisely the same misalignment oscillations in the alpha angle.

There are several possible causes for the observed misalignments:

(1) The first possibility from the geomagnetic point of view is the possible presence of magnetic field contributions that are not represented in field models such as POMME9. These would have to contribute in such a way that the true magnetic field is systematically rotated against the geomagnetic field model. Earth rotation beneath the satellite ensures that any inaccuracies in the internal part of geomagnetic field model average out over the day. So, the source of the rotation would have to be external fields organized in local time, as described in Chapter 4.2 of a preparatory study for the Swarm satellite mission (Olsen et al., 2004). The misalignments in the alpha angle are particularly regular. The orbital plane of the spacecraft drifts by about 1 hour of local time in 11 days. The peaks correspond to times when the spacecraft crosses the equator northward at midnight. The troughs occur when the spacecraft crosses the equator southward at midnight. A possible source of such a magnetic field rotation could be far-fields of field-aligned currents. The latitude range was therefore reduced from initially ±60° to ±30° apex latitude. This reduced the noise slightly but did not change the amplitude of the misalignments in the alpha angle. The corresponding signatures in the eastward magnetic field component (B_y) are displayed in Figure 3a and 3b for CHAMP and Swarm. If such magnetic fields with an amplitude of about 3 nT were indeed present in nature, they would be interpreted by our method as the misalignments in the alpha angle displayed in the top graph of Figure 2. In order to investigate the likelihood of the existence of such natural magnetic fields, Figure 3c shows two hypothetical current configurations, which would generate such signatures in B_y. Since electrical conductivity is low in the night-side ionosphere, there is no obvious cause for such currents. It is nevertheless possible that natural magnetic fields are the source of the observed misalignment signatures.

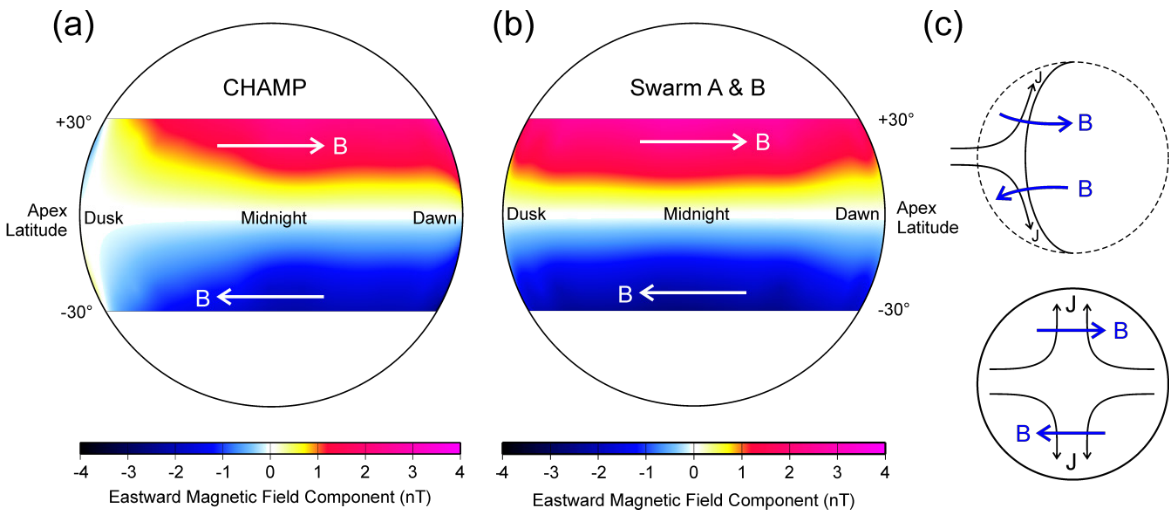

Figure 3: Magnetic fields that would cause apparent misalignments as seen in the top graph of Figure 2 for CHAMP (a) and Swarm (b). The sketches in (c) show possible electrical currents that would give rise to such magnetic fields.

(2) Magnetic fields could also be caused by the spacecraft itself in the form of induced magnetization or thermal currents. However, both CHAMP and Swarm were built to very high levels of magnetic cleanliness and the excellent agreement between the oscillations of the alpha angle between the different spacecraft render this possibility highly unlikely.

(3) Finally, the misalignments could also be due to deficiencies in the software carrying out the star camera aberration correction. For the early CHAMP measurements in the Commissioning Phase, the algorithms were described in detail by Bock and Lühr (2001). To achieve accuracies better than 2 arc seconds, as required for Swarm, aberration should be corrected separately for each star, and the closest stars should either be omitted or corrected for parallax (Shuster, 2003). Because geomagnetic satellite missions do not have sufficient bandwidth to transmit star images, this means that attitude solutions cannot be accurately post-corrected on ground for aberration, but the correction should instead be carried out onboard the S/C as part of the star tracker firmware. For Swarm, the correction is nevertheless being carried out on ground, although the documentation of the Swarm Level-1b processor algorithms mentions the possibility to carry out the corrections on the S/C (Tøffner-Clausen, 2011). Earth orbital motion about the Sun is about 4 times as fast as satellite orbital motion about the Earth and therefore contributes most to aberration. The dashed black lines in Figure 2 show the expected aberration due to orbital movement of the Earth around the sun. For CHAMP and Swarm the average star camera boresights are in the Z direction. For a noon-midnight orbit, the Earth orbital velocity vector is in the Y direction. The cross product of Z with the Earth orbital velocity vector Y component leads to an oscillation with 20 arc seconds in the alpha angle for rotations about X. The observed oscillations in alpha correspond very well in amplitude and phase with the expected effect of an uncorrected aberration. Since one of the cameras is often blinded by the sun, and different combinations of camera heads with different bore sight directions are combined to an attitude solution at different times, it is difficult to predict the aberration effect on the beta and gamma angles. Since CHAMP, Swarm and the geopotential missions GRACE and GOCE employ multi-head star trackers, a deficient aberration correction would be identifiable as apparent local-time-dependent movements of the camera heads relative to each other. Such inter-boresight variations would be an order of magnitude larger than the stated accuracies of the star trackers.

In summary, the geomagnetic satellite missions CHAMP and Swarm for the first time offer the possibility to measure geomagnetic field directions with arc second accuracy. This is about 2 orders of magnitude better than what can be achieved on ground. Such leaps in accuracy offer unique opportunities to validate models of the internal and external geomagnetic field. As described here, a powerful test is to check for the alignment of the geomagnetic and stellar reference frames, which should be steady to within about 2 arc seconds. Instead, oscillating misalignments with over 20 arc second amplitude present themselves as a clear and consistent signal in the measurements of CHAMP and the three Swarm satellites. The excellent agreement between the 3 Swarm satellites confirms the high accuracy of their instrumentation and makes it unlikely that the misalignments are caused by a mechanical instability. Resolving the source of these misalignments could lead to fundamental new insights into the structure of the geomagnetic field. Obtaining a stable alignment will enable an order of magnitude improvement in the calibration of the CHAMP and Swarm magnetometers. Over 30 other science missions employ the same family of star trackers. In case the misalignments can be resolved by an updated stellar aberration correction, these other missions would experience corresponding improvements in attitude accuracy.

Acknowledgements

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