Investigations on SWARM Level 1b star tracker processing, star tracker data quality and GPS tracking analysis

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SWARM, ESA's magnetic field mission launched in November 2013, is incorporating three identical satellites in different orbits to gain enhanced knowledge about the Earth's magnetic field. To reach the goal of a high-resolution model of the Earth's magnetic field it is important to know the exact position and attitude of all satellites and their instruments. By integrating star trackers and GPS equipment on the satellites this information is available for each satellite. Our investigations concentrate on the quality of these observations. We want to implement the official L1b Processing of the star tracker products from the L1a data , including an aberrational correction and a least square adjustment, and compare our result with the official L1b data. In this way we can validate the official implementation of the processing chain. Regarding the GPS instrument, we are interested in the overall performance. Additionally, we found some interesting artefacts linked to the limit of observable satellites.

Star Tracker Attitude analysis

Star Tracker L1b Processing: The main input for the L1b processing are the L1a quaternions of all three star trackers on each satellite. Firstly they have to be corrected for aberration. The aberration is an effect caused by the relative movement of the satellite to the observed stars, which introduces a slight shift of the actual star position. By considering the satellite 's movement around the Earth and the Earth 's movement around the sun (Figure 2a)), this effect can be corrected.
To ensure the quality of the least squares adjustment, we need valid, consistent and of high quality attitude. So the first step before the adjustment is to check the quality and the consistency of the values. Then the adjustment in a least-square sense is implemented for different situations: 3 valid sensors, 2 valid sensors, 1 valid sensor.
The adjustment is realized by using the quaternions CRF to CHU and CHU to ICRF.

Figure 1

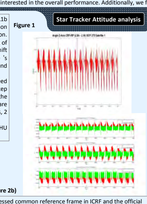

Figure 2a)

Figure 2b)

Figure 1: illustrates the angle between the z-axes of the reprocessed common reference frame in ICRF and the official one for satellite 1. Normally, the difference is from 0 to 0.15 arcsec. and shows a periodic variation. If sensor 3 is invalid, the difference is relatively large. There are still some interesting suspicious values in the difference of the adjustment and the official L1b product. And these errors occur randomly. In the following process this residuals will be investigated.

Figure 2: illustrates the graphical representation of the aberrational effect and the comparison of the interboresight angle of satellite 1 before (red) and after (green) the aberrational correction.
Figure 2a) The velocity of the spacecraft in ICRF frame causes orbital aberration, whereas the Earth's velocity around the Sun causes annual aberration.
Figure 2b): shows a comparison of the interboresight angles: Red points represent original L1a interboresight angles. Green points are interboresight angles after the correction for the aberration. The green dots show less systematics, but a noise level of about +/- 15 arcsec remains.

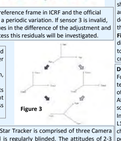

Figure 3

Figure 3 illustrates the different systems in star tracker attitude analysis. The Star Tracker is comprised of three Camera Head Units (CHUs) mounted on the innermost end of the optical. One head is regularly blinded. The attitudes of 2-3 CHUs are combined into one attitude by using least squares adjustment method. After the adjustment the orientation of the combined reference system i.e. common reference frame will be obtained in ICRF.

Figure 4a

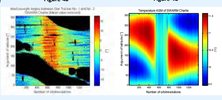

Figure 4b

Figure 4a illustrates the interboresight angles (mean value removed) between the CHUs No. 1 and No.2 on Swarm C while **figure 4b** represents the temperature near the star trackers on Swarm C (some error in the temperature measurement visible between 550 - 800 revoutions). The interboresight angles between 2 sensors should be 90 degree theoretically. However, there exist some anomalies which are somehow correlated to the temperature .
Figure 4a) Interboresight angles (mean value removed) between Star Tracker No.1 and No.2 of Swarm C (if the mean values are deleted, the anomalies should be 0 under ideal conditions. There exist also blind areas. Interboresight angles are affected by temperature. It is a serious problem because it decreases the accuracy of the determination of the satellite's orientation. In the image also some short term variations are visible.
Figure 4b) Temperature on SWARM Charlie: The temperature varies with different orbit revolutions and with different arguments of latitude from 9.5°C to 11.5°C. The temperature affects the structure of interboresight. We will concentrate on this topic in following investigations

Discussion:
For the interboresight angle (IBA) study, we find a relationship between the temperature and the IBA. In the next step of our study, the reason for this kind of influence should be investigated to get a more accurate orientation.
After the aberrational correction systematics decreased, as expected. Still some noise remains in the data.
In the least squares adjustment, there are still some discrepancies between L1b official processing and our adjustment processing. Our algorithms will be checked for remaining discrepancies to the original processing chain. A possible cause might be a slight difference between the time-stamps of our product and the original one. This might cause some periodic differences between our product and the official product.

GPS tracking analysis

Apart from measuring the Earth's magnetic field, the Swarm Mission may also serve as a mission for gravity field determination. Thus, Orbit determination of Swarm satellites through GPS tracking is important. This part focus on the GPS tracking data evaluation and analysis.
Figures 5 i) displays the histogram of the duration of tracking period of GPS satellites for Swarm A in one day (2015.05.01). The histogram shows the distribution of tracking time for all GPS satellites, from which we can see that 35-36 minutes are the most frequent value. Further more, the duration ratio (duration from the beginning of tracking to the closest point divided by duration from extrema to the end of tracking) of each tracking period can be calculated. The histogram of duration ratio indicates that the movement of GPS w.r.t Swarm A are mostly symmetrical, as 1 is the most frequent value, see **Figures 5 ii)** .

Fig 5 i)

Fig 5 ii)

Figures 6 i) indicates the number of tracked GPS satellites along the trajectory of Swarm A on May 1st, 2015. Here we can see that mostly, the tracked GPS number is 5 or 6, and the total tracked number is up to 8, which is only a small part. Based on this, the long period ground track with rare tracked GPS satellites is analyzed. **Figures 6 ii)** shows the ground track of Swarms A within 9 months (2014.08.01-2015.05.03) with the number of tracked GPS satellites less than 7, with Local Time information according to the color bar. Some special patterns can clearly be seen along the geomagnetic equator as well as four repeated fish-like patterns between 25°and 75° latitude, 45°W/E– 105°W/E, 15°W-55°E, and 165 °E-165°W longitude.

Fig 6 i)

Fig 6 ii)

Fig 6 iii)

There are some possible reasons for the special patterns in **Fig.6 ii)**. For the reason of these fish-like patterns, it was found out that the GPS receiver on Swarm do not track satellites which are set to "unhealthy". So if Swarm A sees 8 satellites and two of them are set to "unhealthy", it will just track the remaining six. Patterns around the geomagnetic equator are most probably due to interaction with the ionosphere. **Figure 6 iii)** shows the local time when Swarm A passed different areas on the earth in 9 months, thus the local time change of poor tracking situation can easily be known.

Figure 7 and **8** show the noise analysis of observations on RINEX level. After repeated forming the differences of successive measurement epochs, the noise gets more prominent while deterministic signal almost disappears.

Figure 7 i), ii) show four times differenced L1 signals w.r.t time and latitude for day 110 of 2015. It can be seen that the noise increases periodically in about 45 minutes, and high latitude (>50°) shows large noise.

Figure 8) Double epoch difference of L1 and L2 frequency for different GPS satellites are calculated and ploted (for Swarm A), which indicates a strong correlation (slightly shifted) between these two frequencies.

Fig 7 i)

Fig 7 ii)

Fig 8