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Introduction

Swarm mission constellation, launched into orbit on November 22, 2013, consists of three satellites that precisely measure magnetic signal of the Earth. Each of the three satellites is equipped with three µASC Camera Head Units (CHU) mounted on a common optical bench (OB), which has a purpose of transference of the precisely determined attitude from the star trackers to the vector magnetometer (VFM) measurements.

Although pre-launch analyses were made to minimize thermal and mechanical instabilities of the OB, significant signal with thermal signature is discovered when comparing relative attitude between the three CHU's. These misalignments between CHU's, and consequently geomagnetic reference frame, are found to be correlated with the optical bench temperature variation.

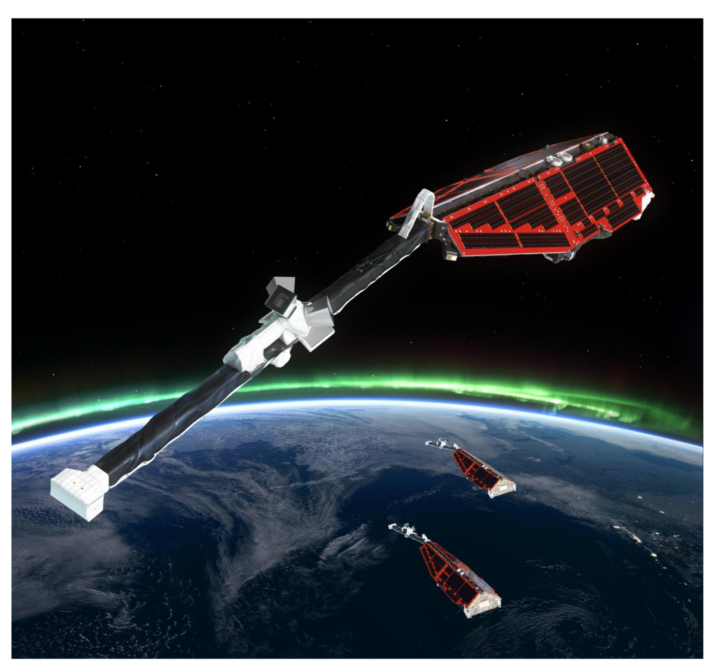
In this paper, we investigate the propagation of thermal effects into the µASC attitude observations and demonstrate how thermally induced attitude variation can be predicted and corrected in the Swarm data processing. The results after applying thermal model significantly improves attitude determination which, after correction, meets the requirements of Swarm satellite mission. This study demonstrates the importance of the OB pre-launch analysis to ensure minimum thermal gradient on satellite optical system and therefore maximum attitude accuracy.

micro Advanced Stellar Compass µASC

- Designed and produced by the Measurement and Instrumentation (DTU)
- to date one of the most successful star tracker worldwide
- autonomously calculates attitude based on all bright stars in the CHUs
- Running a single CHU, µASC can provide 22 true solutions per second
- absolute accuracy of < 1 arc second
- operating on many satellite missions without a single hardware or functional failure

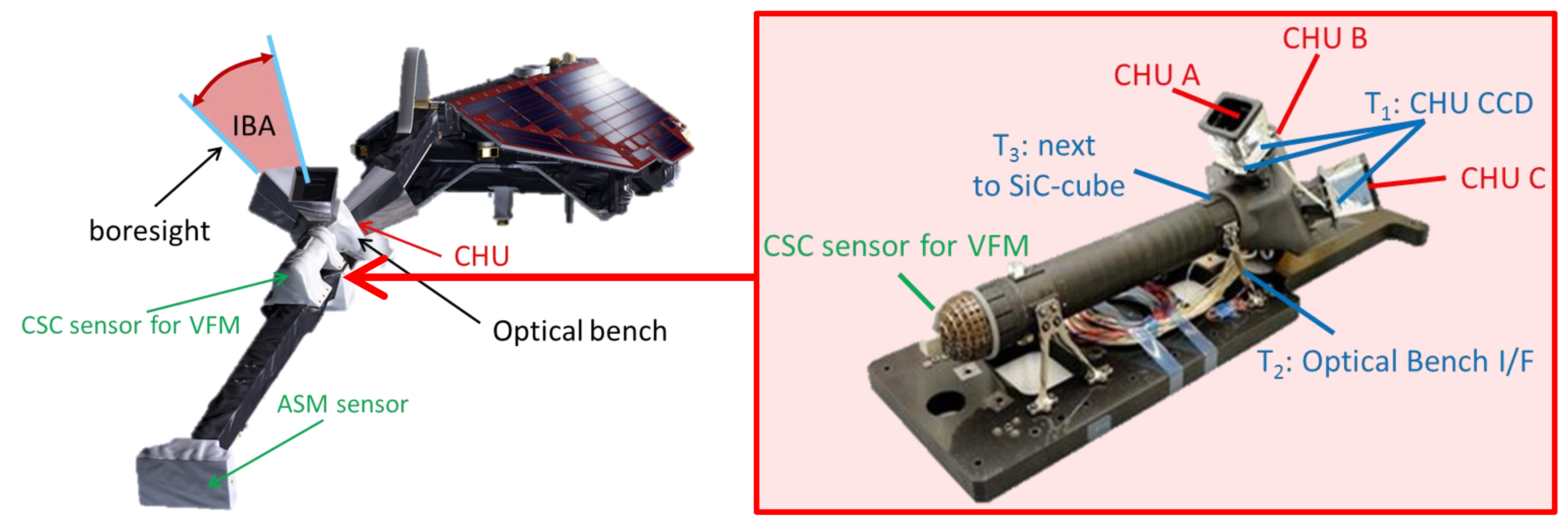
DTU Space µASC

µASC baffle



Swarm satellites in orbit with a view of Optical Bench

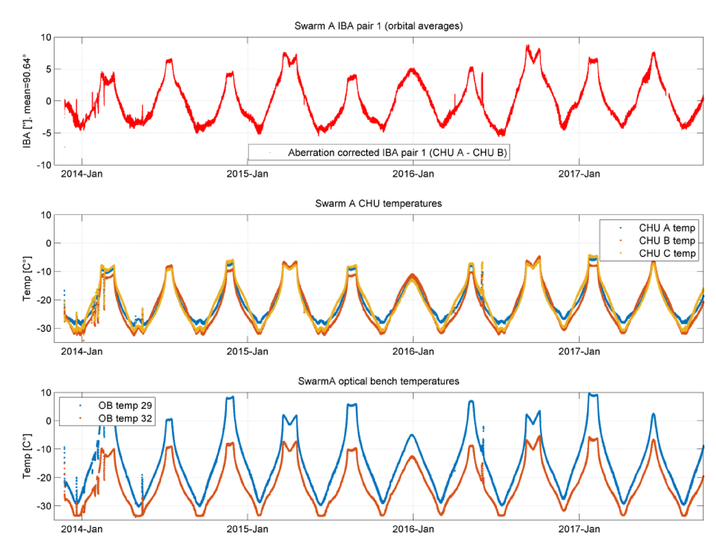
Swarm optical Bench



Swarm optical bench (OB) is an ultra-stable silicon carbide-carbon fiber compound structure installed on a deployable conical tube of square cross section. Its purpose is transference of the precisely determined attitude using star trackers to the magnetometer field components.

Observed thermo-elastic instabilities

The three CHU's are placed on OB and arranged with the Inter Boresight Angle (IBA) of around 90º from each other. Ideally, IBA is expected to be constant. However, IBA variation shows periodicity, which is correlated with temperatures measured on three Swarm satellites.



The fixed frame is defined as:

$$Z_F = \frac{Z_A \times Z_C}{|Z_A \times Z_C|} \quad X_F = \frac{\frac{Z_A+Z_C}{2}}{\left|\frac{Z_A+Z_C}{2}\right|} \quad Y_F = \frac{Z_F \times X_F}{|Z_F \times X_F|}$$

Each rotation is described by:

$$R_1(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

$$R_2(\beta) = \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix}$$

$$R_3(\gamma) = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

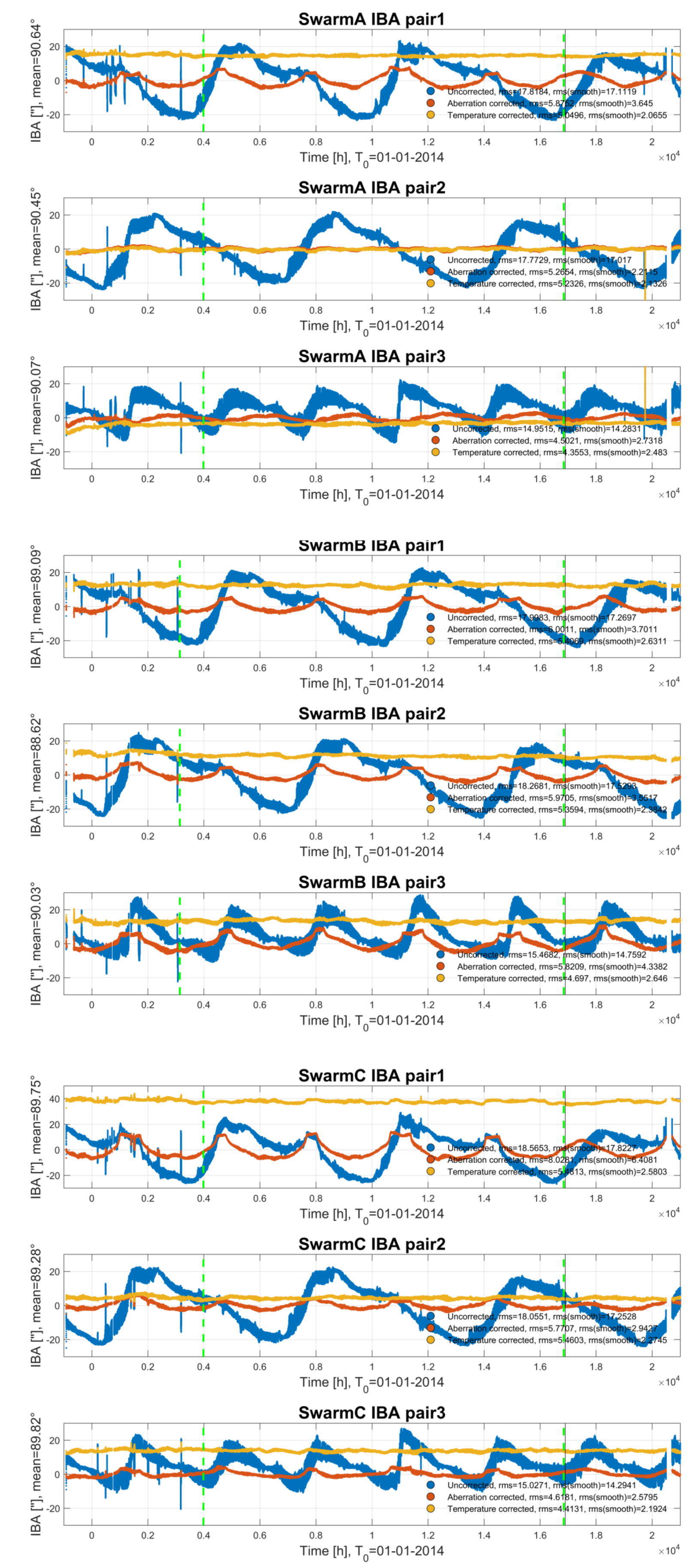
Thermal model is found by Singular Value Decomposition (SVD) fitting of IBA orbital averages and observed temperatures, and it describes how each CHU moves relative to its pre-light calibrated frame due to the thermal gradients. It is defined as:

$$R_{CHUcorrected} = R_3(\gamma)\, R_2(\beta) R_1(\alpha) R_{CHU}$$

Individual rotation angles:

$$\alpha = \alpha_0 + \alpha_1 T_1 + \alpha_2 (T_2 - T_1) + \alpha_3 (T_3 - T_1)$$
$$\beta = \beta_0 + \beta_1 T_1 + \beta_2 (T_2 - T_1) + \beta_3 (T_3 - T_1)$$
$$\gamma = \gamma_0 + \gamma_1 T_1 + \gamma_2 (T_2 - T_1) + \gamma_3 (T_3 - T_1)$$

Results



	CHU A			
	alpha	beta	gamma	
Constant	-4.67067e-01	+4.59718e-01	+2.36543e-01	["]
T_{CHU_A}	+3.58190e-03	-3.52161e-03	-7.31744e-01	["/°C]
$T_{029} - T_{CHU\_A}$	-9.04363e-03	+8.89788e-03	+4.50041e-01	["/°C]
$T_{032} - T_{CHU\_A}$	-1.04154e-01	+1.02497e-01	-1.12265e+00	["/°C]
	CHU B			
	alpha	beta	gamma	
Constant	-1.19000e+00	+2.03750e+00	+5.51564e+00	["]
T_{CHU_B}	+3.27044e-01	-4.03134e-01	-3.12725e-02	["/°C]
$T_{029} - T_{CHU\_B}$	-2.10603e-01	+4.04762e-02	-7.31304e-01	["/°C]
$T_{032} - T_{CHU\_B}$	+2.40148e-01	+6.57657e-02	+2.07894e+00	["/°C]
	CHU C			
	alpha	beta	gamma	
Constant	+4.08584e-02	+2.99157e-02	+1.17996e+01	["]
T_{CHU_C}	+1.36145e-02	+9.95873e-03	-2.01007e-01	["/°C]
$T_{029} - T_{CHU\_C}$	+1.57687e-02	+1.15304e-02	+4.97267e-01	["/°C]
$T_{032} - T_{CHU\_C}$	+8.06663e-03	+5.89875e-03	+2.25162e+00	["/°C]

IBA 1 (A-B)	Swarm Alpha	Swarm Bravo	Swarm Charlie
Original	17.1119	17.2697	17.8227
Abr. Corr.	3.6450	3.7011	6.4081
Temp. Corr	2.0655	2.6311	2.5803
IBA 2 (A-B)	Swarm Alpha	Swarm Bravo	Swarm Charlie
Original	17.0170	17.5293	17.2528
Abr. Corr.	2.2115	3.5517	2.9427
Temp. Corr	2.1326	2.3842	2.2745
IBA 3 (A-B)	Swarm Alpha	Swarm Bravo	Swarm Charlie
Original	14.2831	14.7592	14.2941
Abr. Corr.	2.7318	4.3382	2.5795
Temp. Corr	2.4830	2.6460	2.1924

Discussion

The analysis and thermal model presented herein, shows that the origin of the IBA variation is thermal gradient driven, and fully recoverable by a simple thermal model.

We present the model for correction of the thermo-elastic instabilities on Swarm satellites optical benches, which cause misalignments between the CHU's relative orientation.

The results after applying thermal corrections show decrease in RMS for all thre Swarm satellites. Therefore, the technique presented here shows improvement in attitude determination which, after correction, meets the 2-arcsecond requirements of Swarm satellite mission.

Presented model is now being implemented in the Swarm data processing.

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