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Swarm ASC Star tracker In-flight status and performance

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Swarm µASC Star tracker In-flight status and performance

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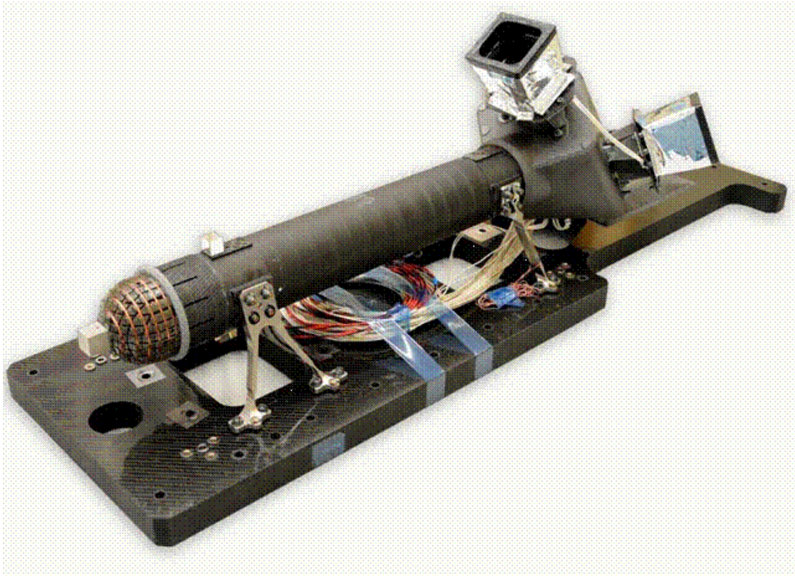
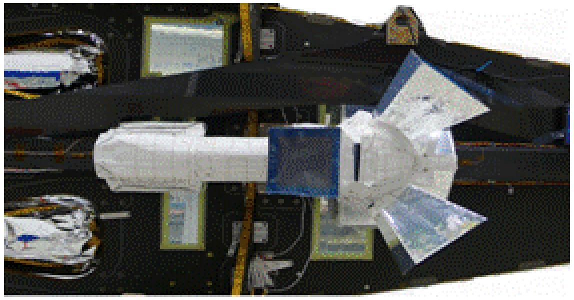




DTU Space
National Space Institute

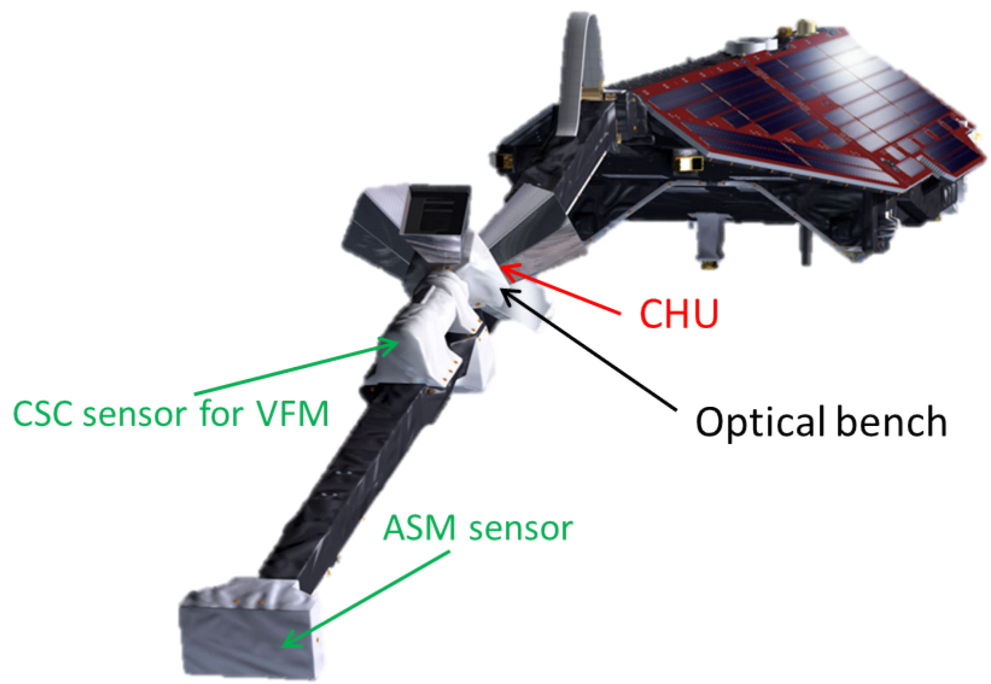
Star Tracker (STR) - μASC

- μASC (micro Advanced Stellar Compass) autonomously calculates attitude based on all bright stars in the Field of View (FOV)

- Running a single CHU, μASC can provide 22 true solutions per second, with absolute accuracy of < 1 arc second

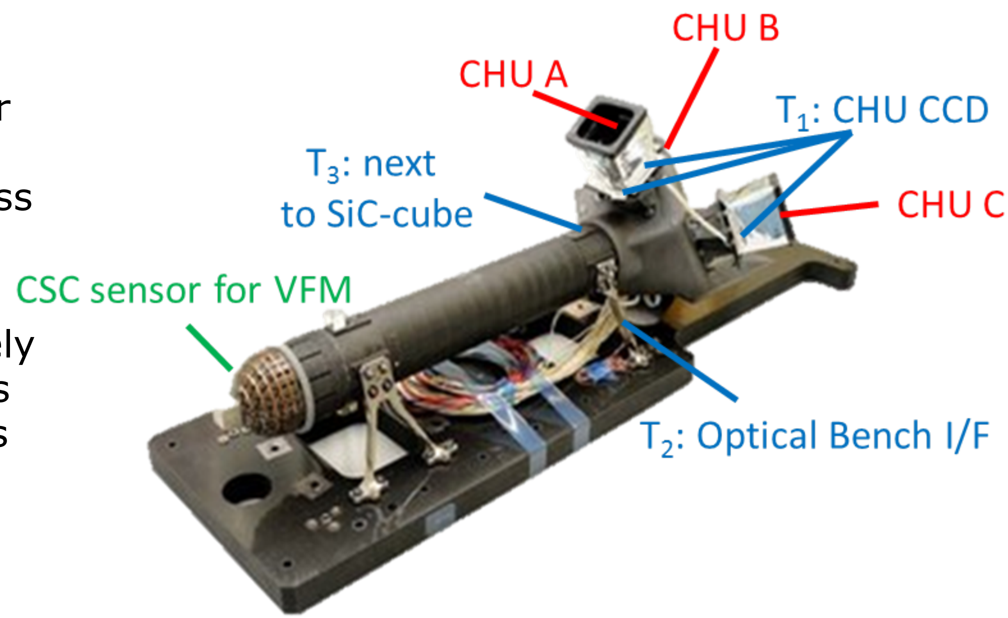
- Three of the μASC, together with the VFM instrument, are mounted on the Swarm OB to provide correct orientation of the VFM and high accuracy of measured magnetic field components.

- objective of VFM is to measure the magnetic field vector



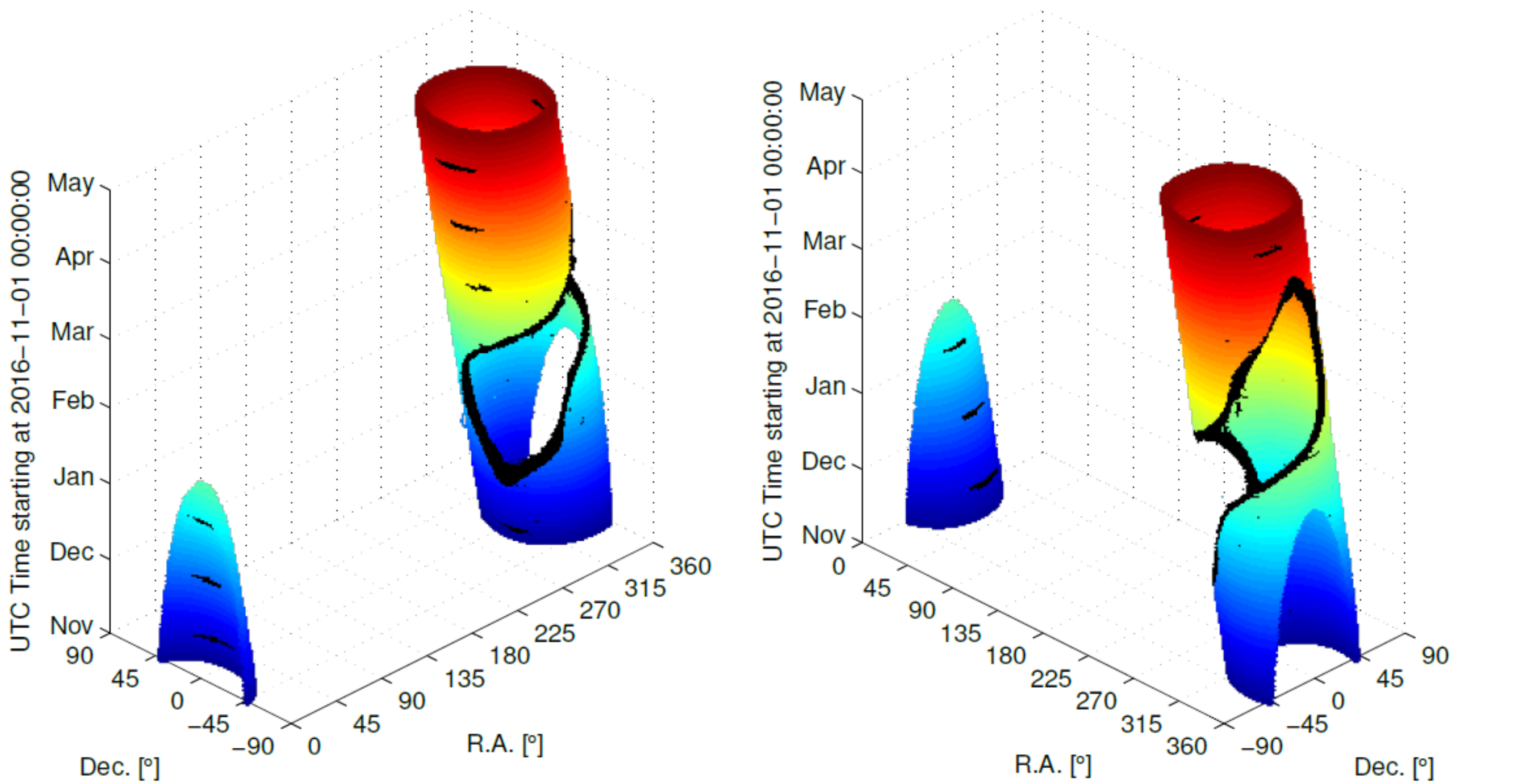
Swarm Optical Bench (OB)

- ultra-stable silicon carbide-carbon fiber compound structure installed on a deployable conical boom of square cross section
- main purpose is to transfer the precisely determined attitude using star trackers to the magnetometer field components
- several thermistors are mounted on different parts of Deployable Boom Assembly (DBA).



Star Tracker (STR):
Availability

Data 2016/11/01 to 2017/04/30



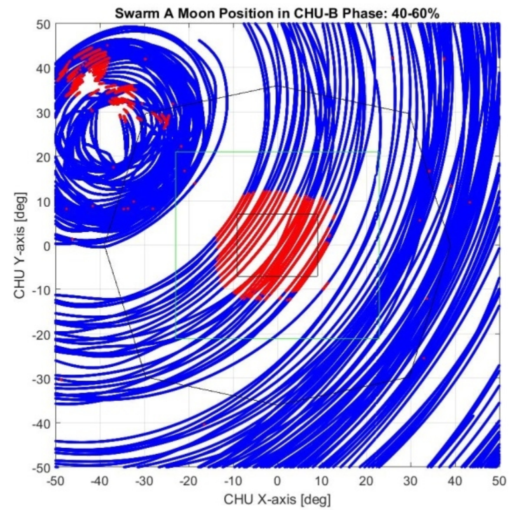
Right Ascension and Declination for Swarm A, CHU C over time. Black attitudes indicate BBO flags.

Star Tracker (STR):
Availability of 2 or 3 sensor solutions

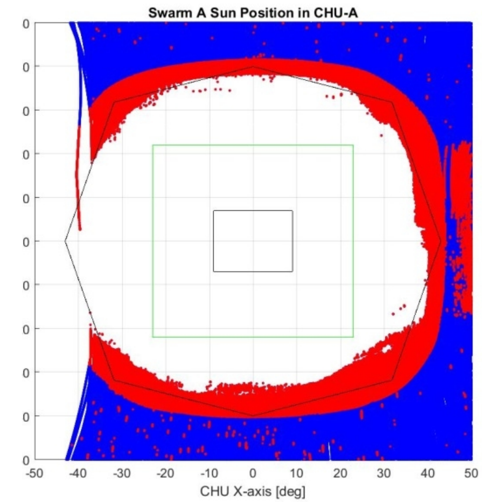
A Star Tracker measurement accuracy is best across the boresight direction. The Swarm STR is using three sensors to eliminate the higher measurement error about the boresight by combining the measurement from 2 or 3 sensors.

- Inflight performance of the sensor baffle systems are better than designed
- Inflight performance towards a 50% Moon show full resilience

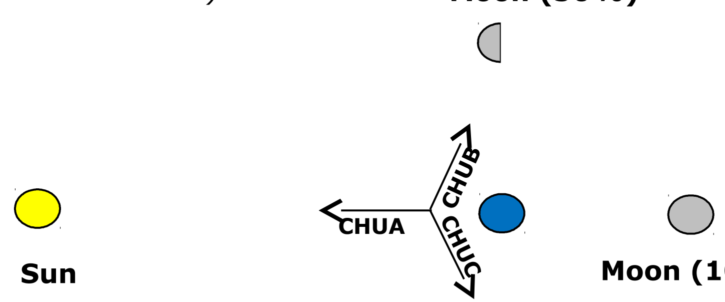
Demonstrating that 2 or 3 sensor solutions are granted, with excellent margins, for the planned mission profile.



Operations vs Moon:
Position of 40-60% Moon in Swarm A CHU-B, Valid attitudes, with BBO flag(red), 184 days data (2015-121 -> 304)



Baffle performance vs Sun:
Position of Sun in Swarm A CHU-A, Valid attitudes, with BBO flag(red), 184 days data (2015-121 -> 304)



Swarm in orbit around Earth

Baffle performance: Swarm Sun Exclusion cones

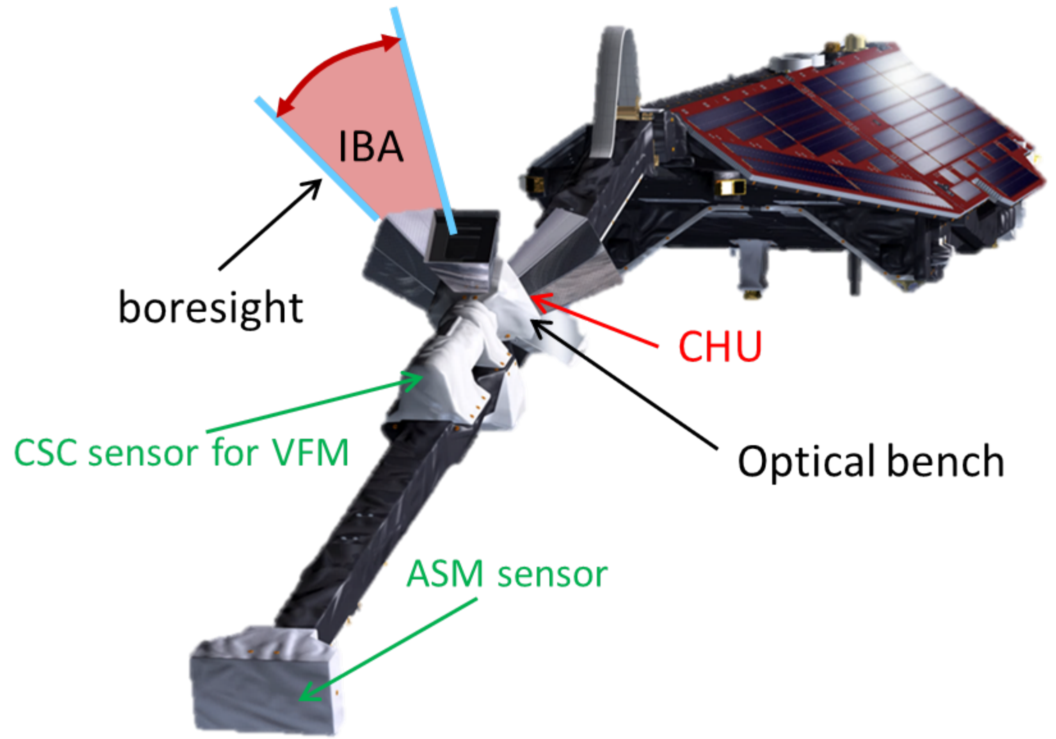
Swarm satellite

- CHU – Camera Head Unit
- IBA – Inter Boresight Angle

- Full accuracy achieved whenever two or three simultaneous valid CHU quaternions are available

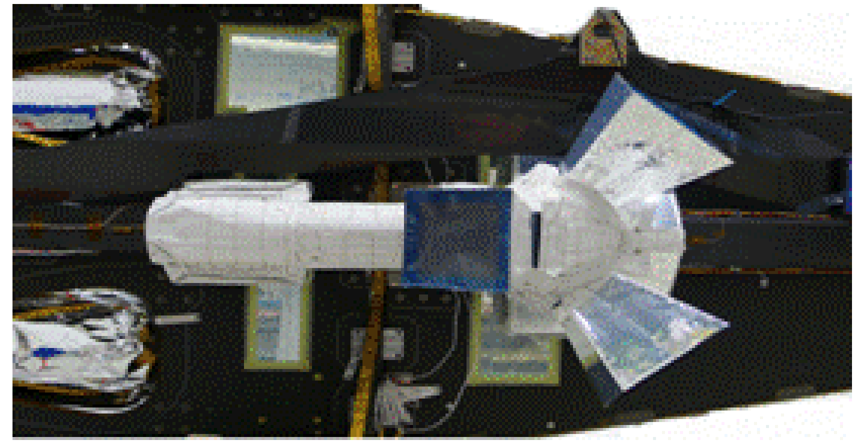
- IBA is treated in CHU pairs:
  - Pair 1: A & B
  - Pair 2: A & C
  - Pair 3: B & C

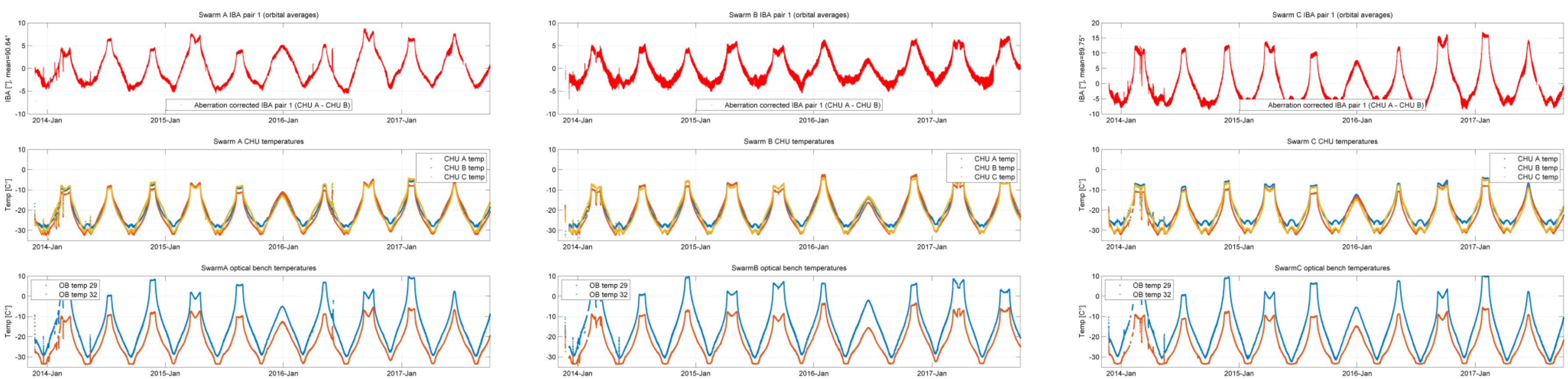
- Ideally IBA is expected to be constant (after aberration correction)



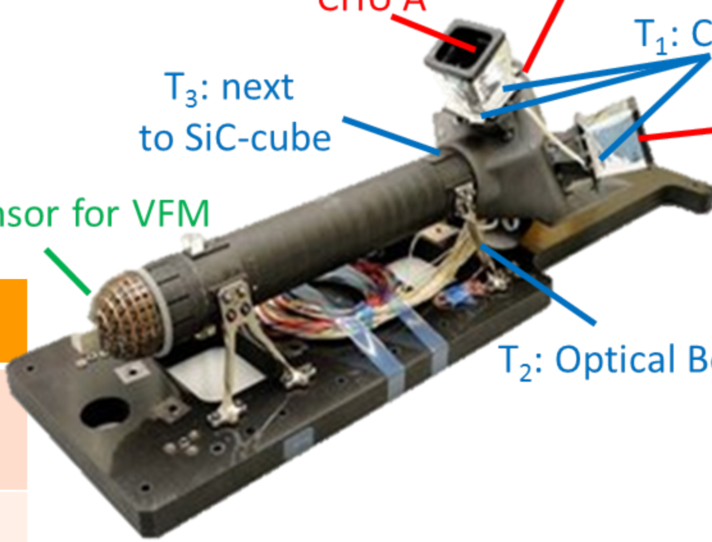
STR Performance Status

Optical Bench and Stand-off Thermo-Elastic Model





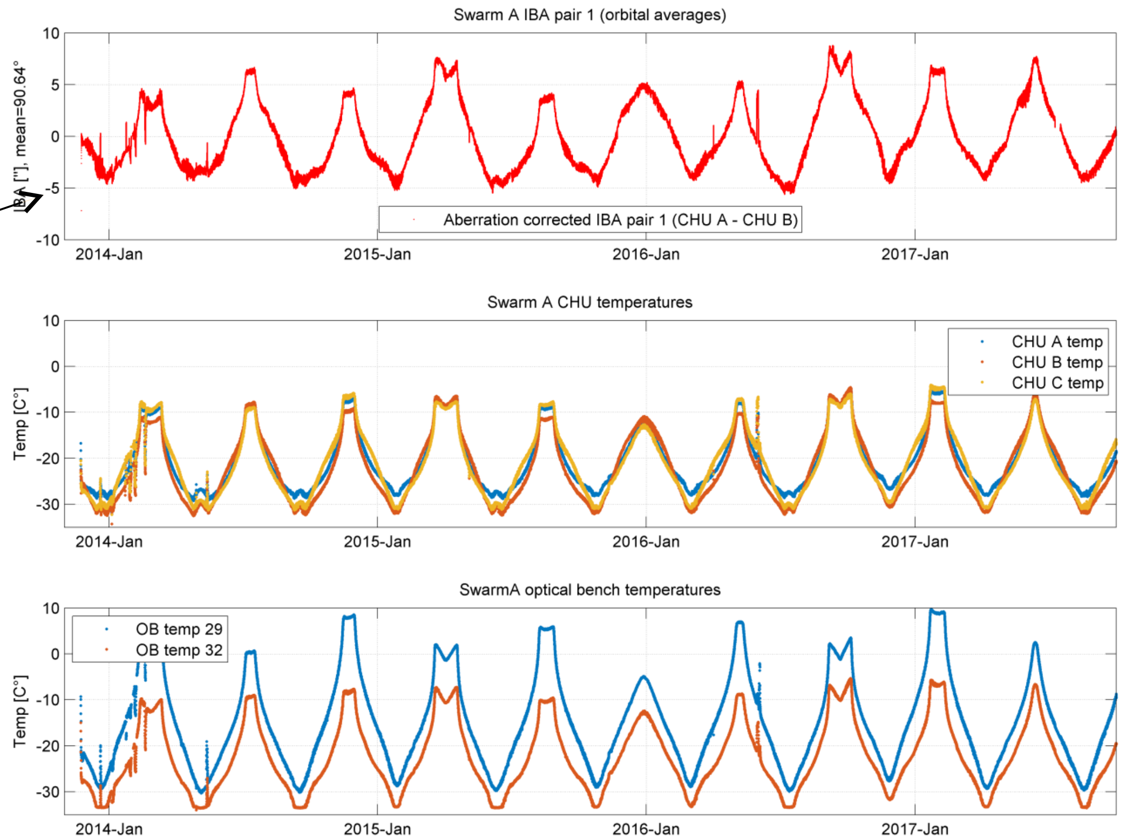
Swarm Optical Bench (OB)



Thermistor name	Thermistor code 1	Thermistor name 2
Hinge	THT00028 THT00056 THT00086	TCL_2_ANY_13A_HINGEHNR TCL_4_ANY_13B_HINGEHNR TCL_6_ANY_13C_HINGEHNR
Optical bench Boom I/F	**THT00029 (T2)** THT00057 THT00087	TCL_2_ANG_14A_OBBOOMIF TCL_4_ANG_14B_OBBOOMIF TCL_6_ANG_14C_OBBOOMIF
Absolute Scalar Magnetometers (ASMS)	THT00031 THT00059 THT00089	TCL_2_ANG_16A_ASMS TCL_4_ANG_16B_ASMS TCL_6_ANG_16C_ASMS
Optical Bench STRH	**THT00032 (T3)** THT00060 THT00090	TCL_2_ANG_17A_OBSUBSYS TCL_4_ANG_17B_OBSUBSYS TCL_6_ANG_17C_OBSUBSYS

Swarm A: IBA and temperatures

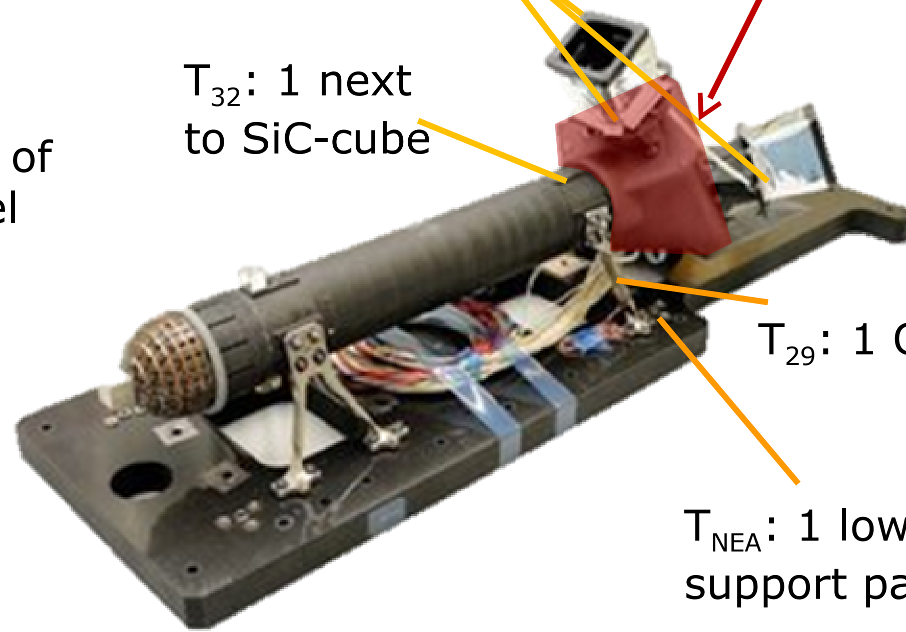
- Apply aberration correction to individual CHU attitudes
- IBA Orbital average
- SC Temperatures
  - CHU
  - Optical bench



Investigating the temperature profiles

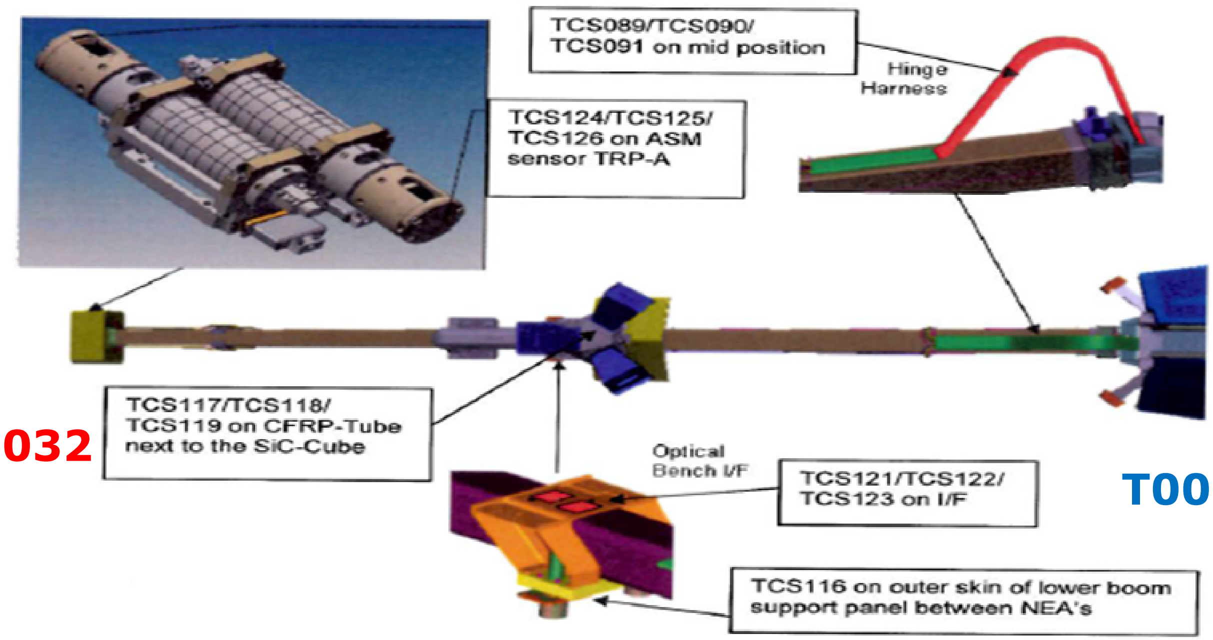
Temperature sensor locations:

- 1 sensor per CHU located at CCD
- 1 sensor at optical bench
- 1 sensor next to the SiC-Cube
- 1 sensor at on outer skin of lower boom support panel between NEA's



Spacecraft thermistor temperatures

- Telemetered Temperatures from the optical bench



T00032

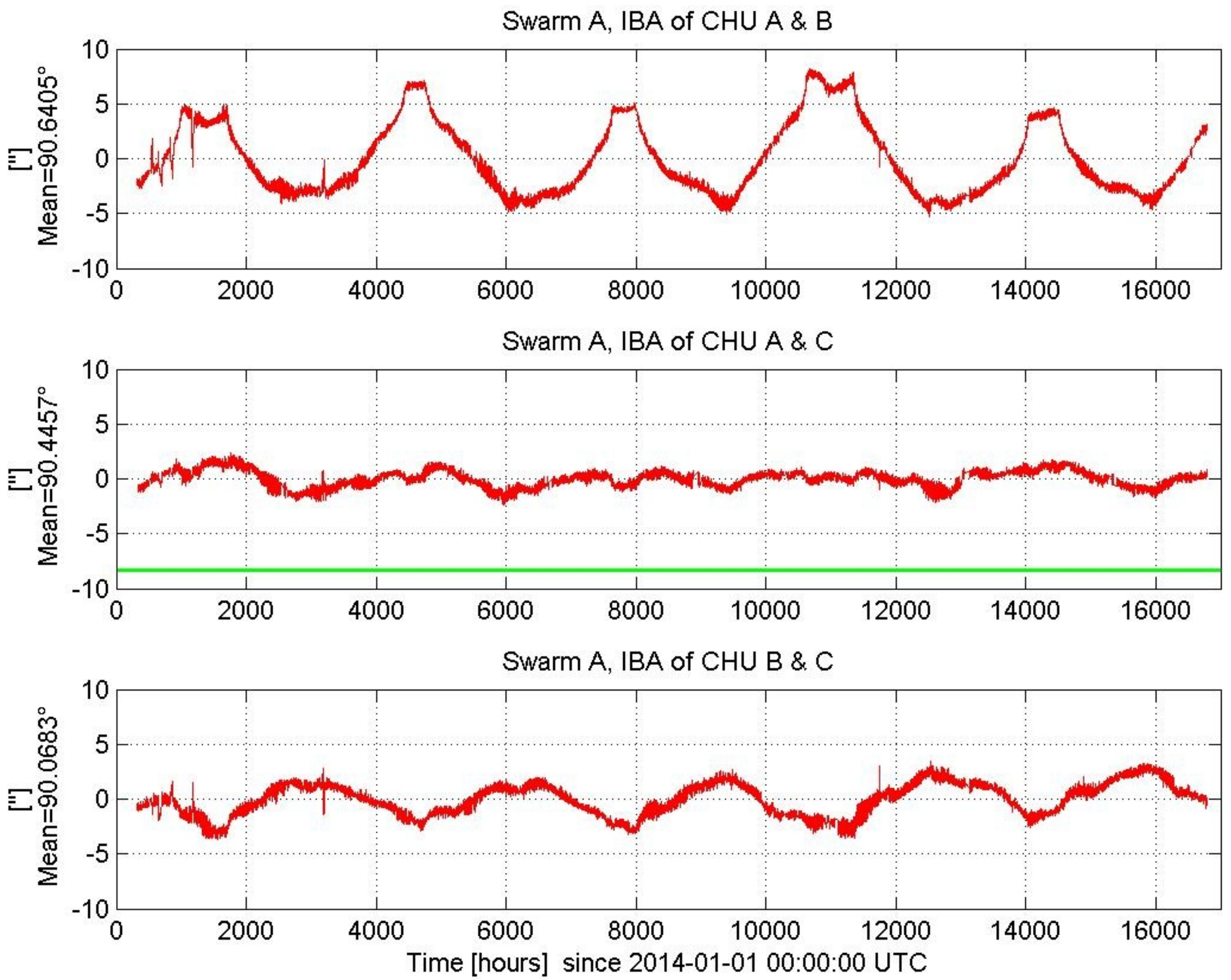
T00029

TH-TCS116	YSI-44907	NEA	Monitor	TH81	TCM_8_ANY_NeaOb	THT00115
TH-TCS117	311P18-03-T-101	Optical Bench STRH-1	Control	TH26	TCL_2_ANG_17A_ObSubsys	THT00032
TH-TCS118	311P18-03-T-101	Optical Bench STRH-2	Control	TH46	TCL_4_ANG_17B_ObSubsys	THT00060
TH-TCS119	311P18-03-T-101	Optical Bench STRH-3	Control	TH66	TCL_6_ANG_17C_ObSubsys	THT00090
TH-TCS120	YSI-44907	CGPS Pressure Transducer (LPT_A)	Monitor	TH5E	TCM_5_ANY_CgpsLptA	THT00082
TH-TCS121	311P18-03-T-101	Optical Bench Boom I/F	Control	TH23	TCL_2_ANG_14A_ObBoomIf	THT00029
TH-TCS122	311P18-03-T-101	Optical Bench BoomI/F	Control	TH43	TCL_4_ANG_14B_ObBoomIf	THT00057
TH-TCS123	311P18-03-T-101	Optical Bench Boom I/F	Control	TH63	TCL_6_ANG_14C_ObBoomIf	THT00087

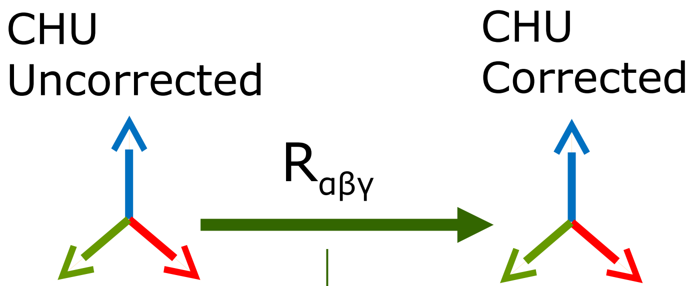
Courtesy of ESA

Swarm IBA pairs

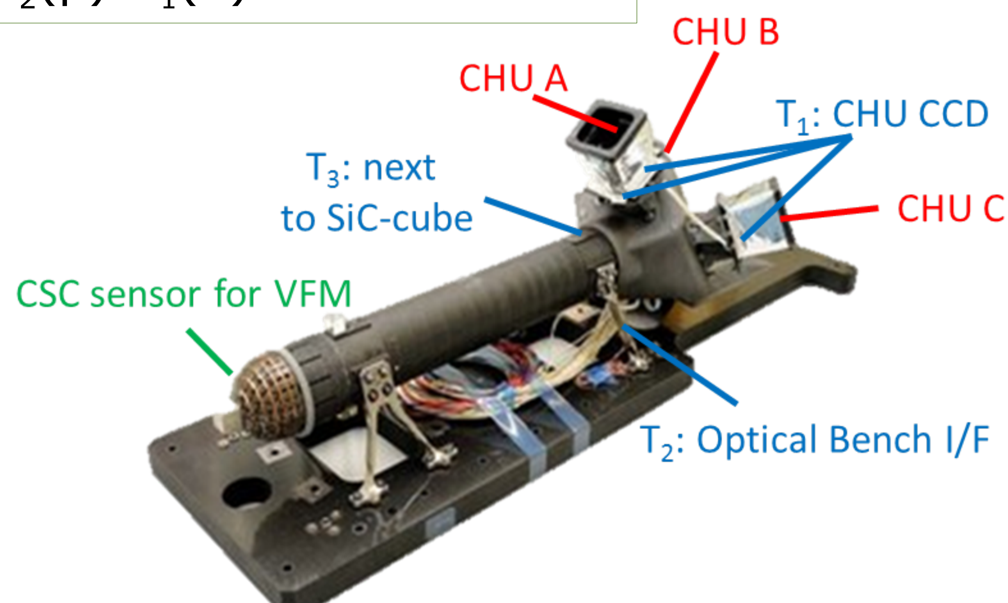
- IBA between CHU A and CHU C does not show clear variation with temperature



Swarm thermal correction model formulation



Model of 3 Euler angles about CHU X-Y-Z axes:
$R_{model}(T_1, T_2, T_3) = R_3(\gamma)\, R_2(\beta)\, R_1(\alpha)$



$$\alpha = \alpha_0 + \alpha_1 T_1 + a_2(T_2 - T_1) + \alpha_3(T_3 - T_1)$$
$$\beta = \beta_0 + \beta_1 T_1 + \beta_2(T_2 - T_1) + \beta_3(T_3 - T_1)$$
$$\gamma = \gamma_0 + \gamma_1 T_1 + \gamma_2(T_2 - T_1) + \gamma_3(T_3 - T_1)$$

Swarm A model

__Modelling period:__

16-Jun-2014 01:38:29 (2014-167)

~4000h

to

03-Dec-2015 21:48:34 (2015-337)

~17000h

Swarm A Fixed Frame Type=16

CHU A

	alpha	beta	gama	
Constant	-4.67067e-01	4.59718e-01	2.36543e-01	["]
T_CHU_A	3.58190e-03	-3.52161e-03	-7.31744e-01	["/°C]
T029 - T_CHU_A	-9.04363e-03	8.89788e-03	4.50041e-01	["/°C]
T032 - T_CHU_A	-1.04154e-01	1.02497e-01	-1.12265e+00	["/°C]

CHU B

	alpha	beta	gama	
Constant	-1.19000e+00	2.03750e+00	5.51564e+00	["]
T_CHU_B	3.27044e-01	-4.03134e-01	-3.12725e-02	["/°C]
T029 - T_CHU_B	-2.10603e-01	4.04762e-02	-7.31304e-01	["/°C]
T032 - T_CHU_B	2.40148e-01	6.57657e-02	2.07894e+00	["/°C]

CHU C

	alpha	beta	gama	
Constant	4.08584e-02	2.99157e-02	1.17996e+01	["]
T_CHU_C	1.36145e-02	9.95873e-03	-2.01007e-01	["/°C]
T029 - T_CHU_C	1.57687e-02	1.15304e-02	4.97267e-01	["/°C]
T032 - T_CHU_C	8.06663e-03	5.89875e-03	2.25162e+00	["/°C]

Swarm B model

Swarm B Fixed Frame Type=16

Modelling period:

12-May-2014 01:00:05 (2014-131)

~3000h

to

03-Dec-2015 22:18:07 (2015-337)

~17000h

CHU A

	alpha	beta	gama	
Constant	1.52156e+00	-1.51290e+00	2.33865e+00	["]
T_CHU_A	-1.22241e-01	1.21530e-01	-1.82904e-01	["/°C]
T029 - T_CHU_A	-9.88533e-03	9.83054e-03	7.01522e-02	["/°C]
T032 - T_CHU_A	-6.98540e-03	6.93775e-03	-7.99214e-02	["/°C]

CHU B

	alpha	beta	gama	
Constant	-5.15861e+00	-1.26225e+00	-2.48957e+00	["]
T_CHU_B	5.28498e-01	1.34662e-01	3.97005e-01	["/°C]
T029 - T_CHU_B	-5.56507e-02	1.06394e-01	-4.76603e-01	["/°C]
T032 - T_CHU_B	4.83616e-01	1.56951e-02	1.14448e+00	["/°C]

CHU C

	alpha	beta	gama	
Constant	-1.57776e+00	-1.10393e+00	-1.74405e+01	["]
T_CHU_C	1.40689e-01	9.83403e-02	1.03966e+00	["/°C]
T029 - T_CHU_C	-1.98237e-02	-1.38350e-02	-9.67086e-01	["/°C]
T032 - T_CHU_C	8.24705e-02	5.76762e-02	-1.41618e-02	["/°C]

Swarm C model

Modelling period:

16-Jun-2014 01:38:17 (2014-167)

~4000h

to

03-Dec-2015 21:48:27 (2015-337)

~17000h

Swarm C Fixed Frame Type=16

CHU A

	alpha	beta	gama	
Constant	5.97502e-01	-5.85954e-01	-2.43077e+00	["]
T_CHU_A	-5.37921e-02	5.27412e-02	-4.39993e-02	["/°C]
T029 - T_CHU_A	-7.50021e-02	7.35446e-02	5.29397e-01	["/°C]
T032 - T_CHU_A	4.28406e-02	-4.20199e-02	-1.28559e+00	["/°C]

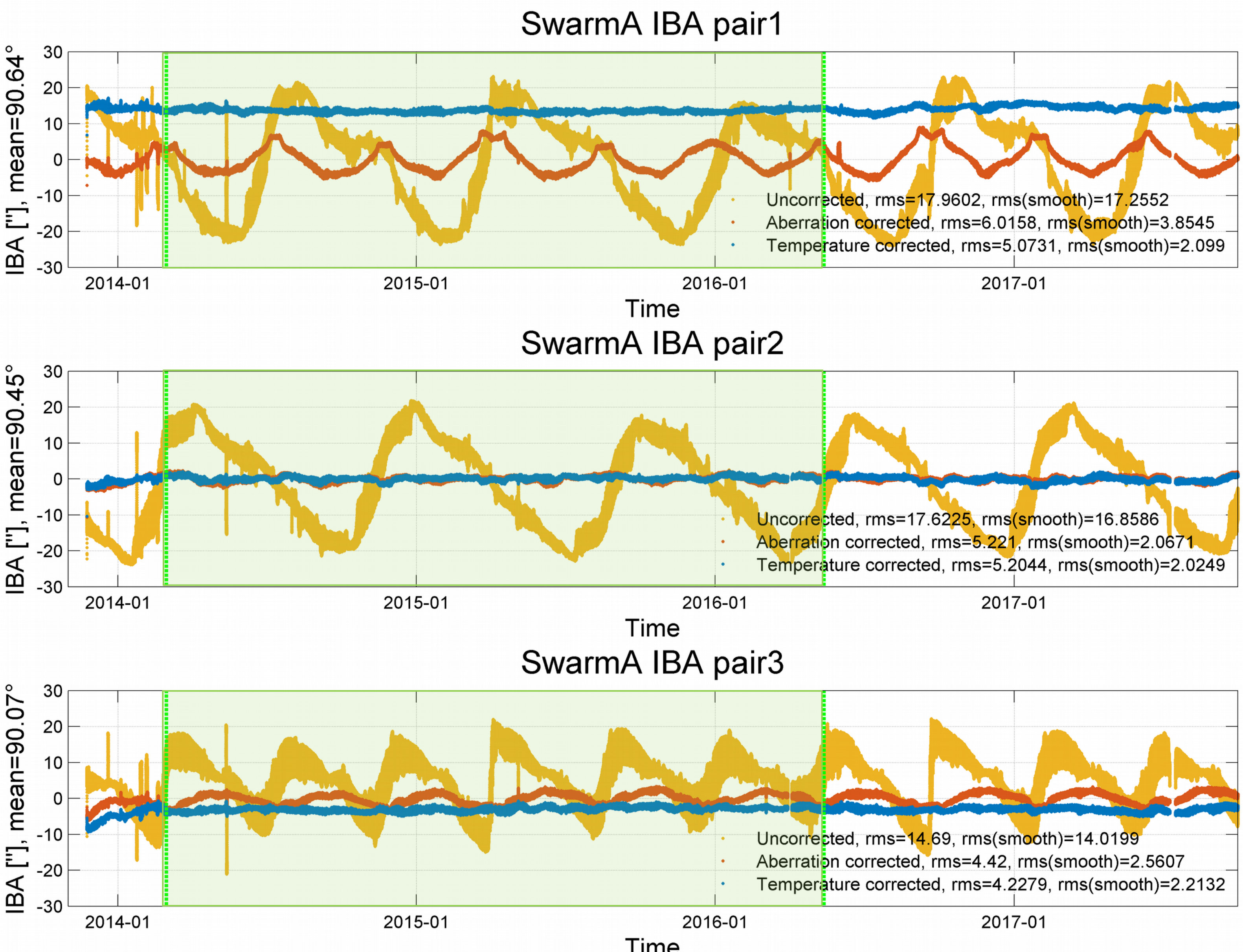
CHU B

	alpha	beta	gama	
Constant	-1.10869e+01	3.34004e+00	3.39132e-02	["]
T_CHU_B	9.87206e-01	-3.09247e-01	-2.03671e-01	["/°C]
T029 - T_CHU_B	-5.47234e-01	1.68646e-02	1.37838e+00	["/°C]
T032 - T_CHU_B	1.10733e+00	-2.25563e-01	-2.05729e+00	["/°C]

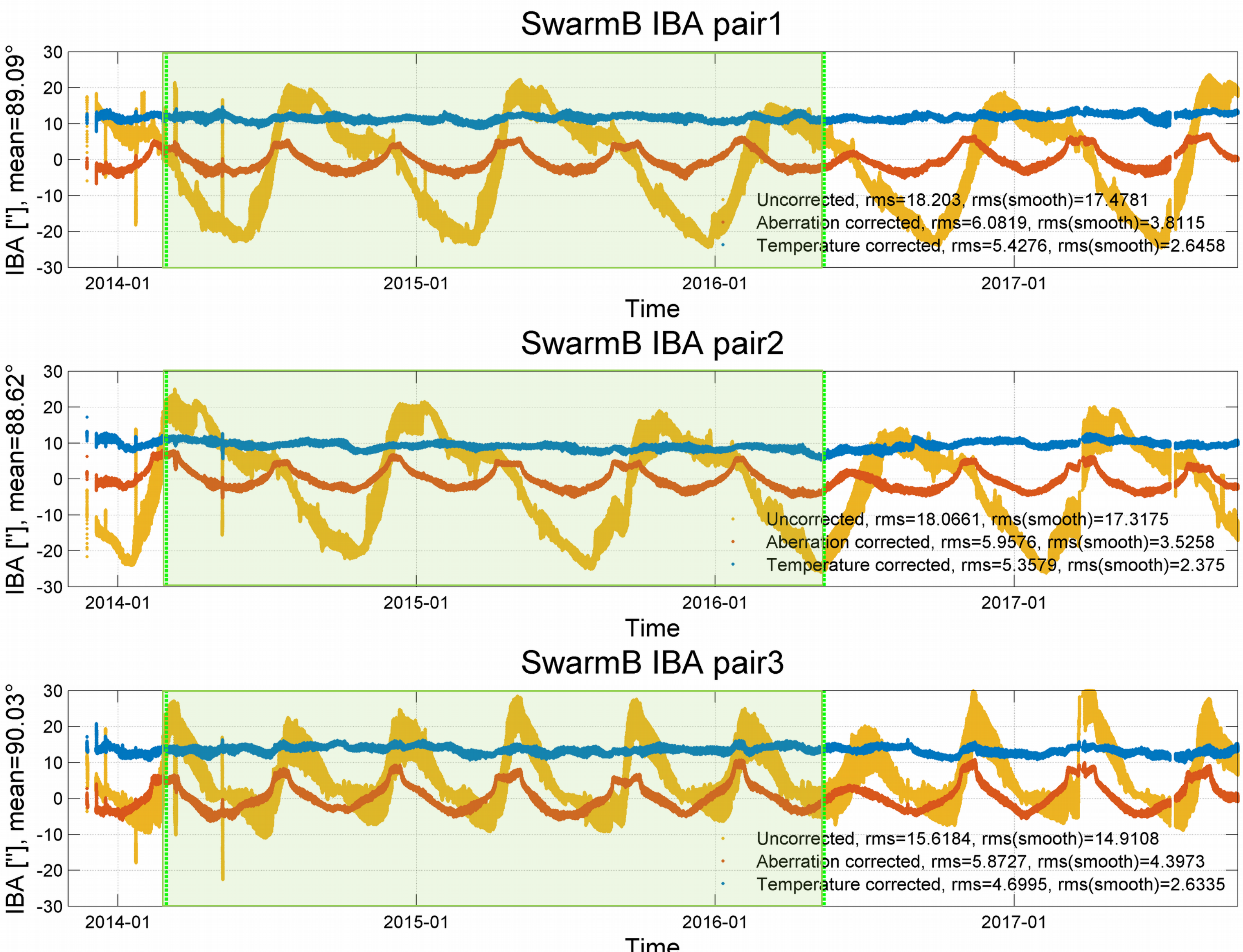
CHU C

	alpha	beta	gama	
Constant	-1.09210e+00	-7.38447e-01	-2.43118e+00	["]
T_CHU_C	7.86517e-02	5.31523e-02	6.91483e-01	["/°C]
T029 - T_CHU_C	5.69351e-02	3.84922e-02	-7.40293e-01	["/°C]
T032 - T_CHU_C	-6.45442e-02	-4.36648e-02	2.46625e+00	["/°C]

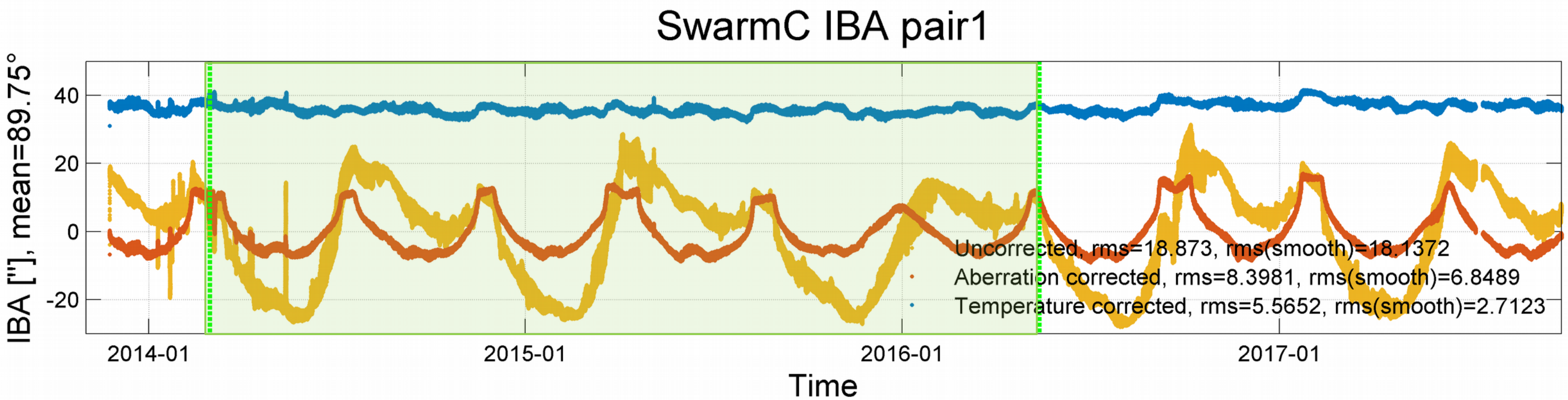
Correction effects Swarm A IBAs

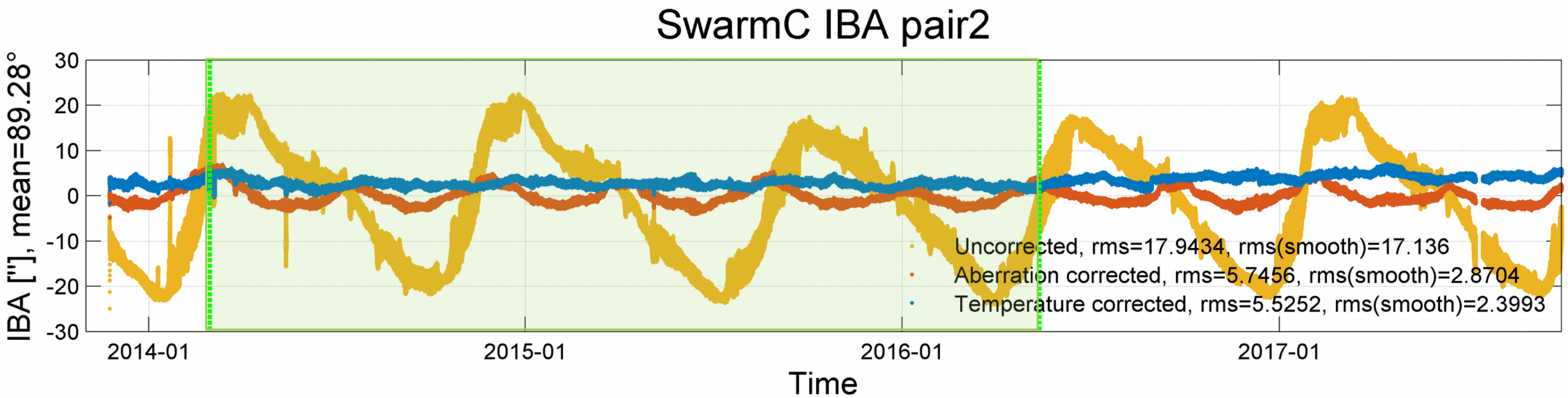


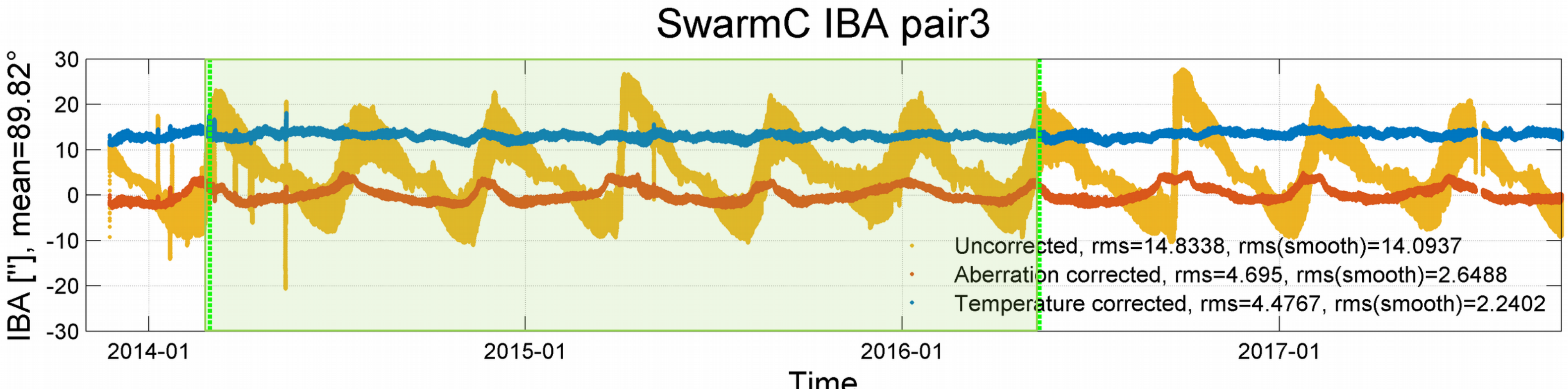
Correction effects Swarm B IBAs



Correction effects Swarm C IBAs





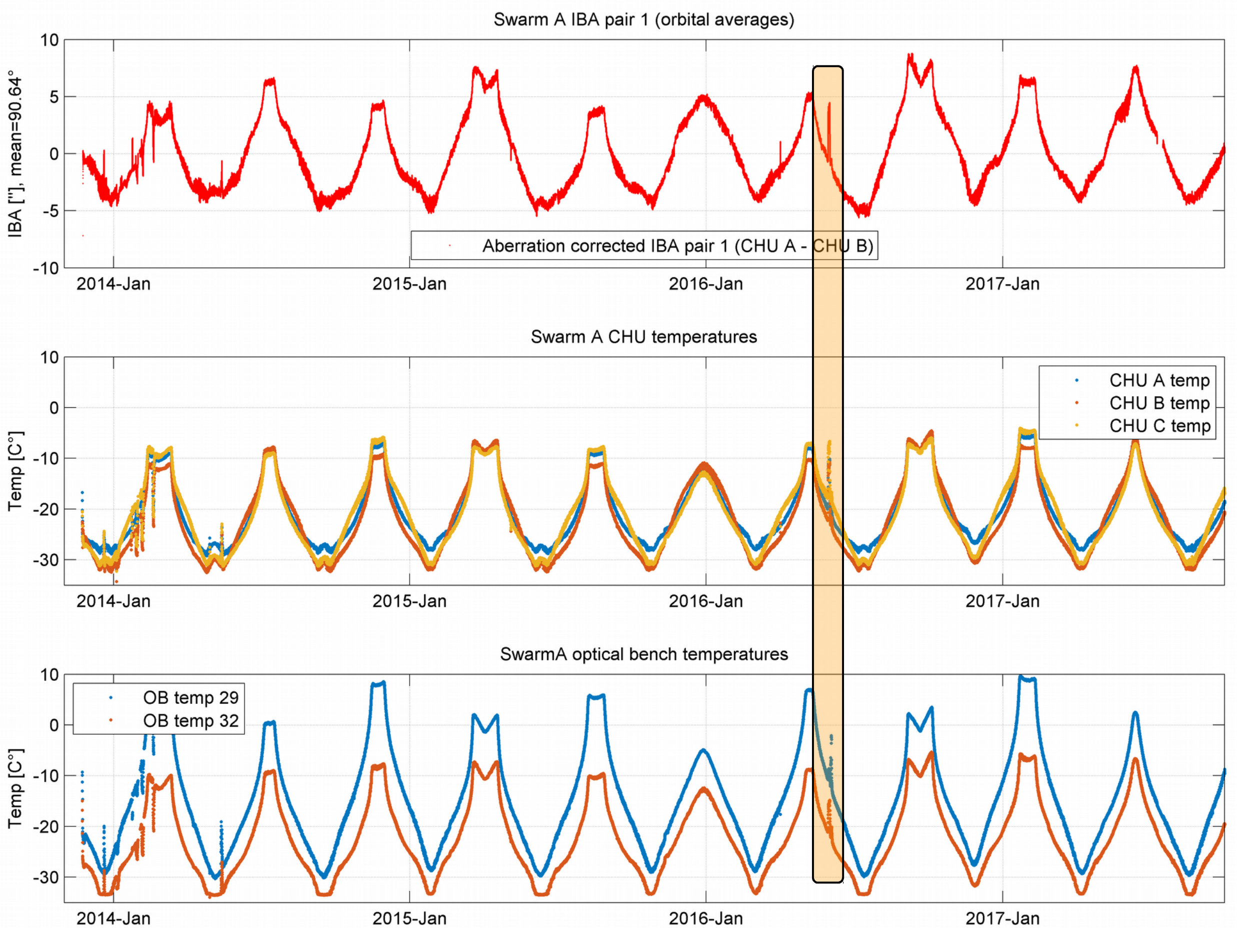


Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)

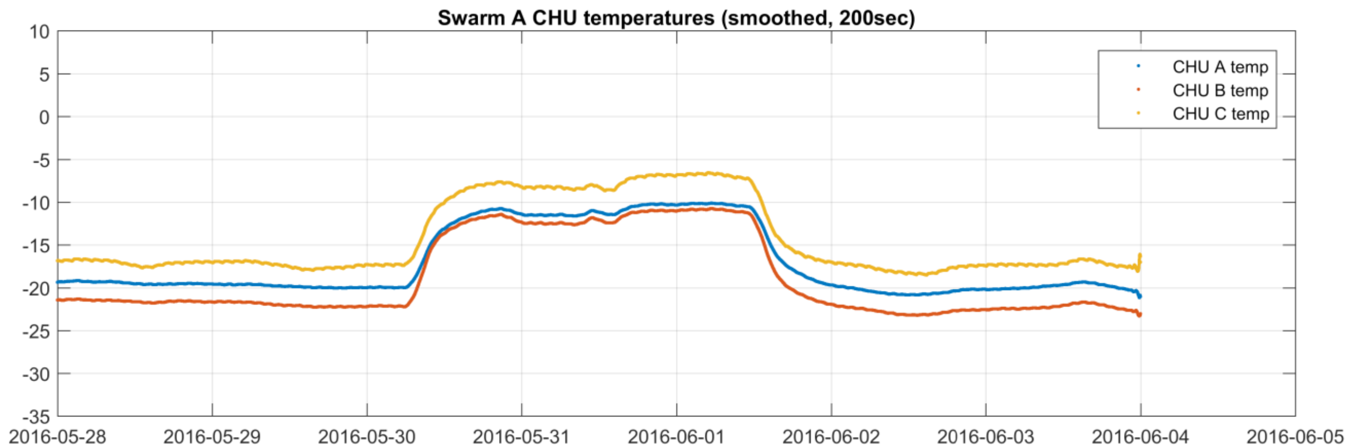
- Two heaters located around the optical bench (OB)
  - an operational heater (id 21) mounted on the radiator plate of the OB,
  - a powerful survival heater (id 01) located on the OB interface bracket.

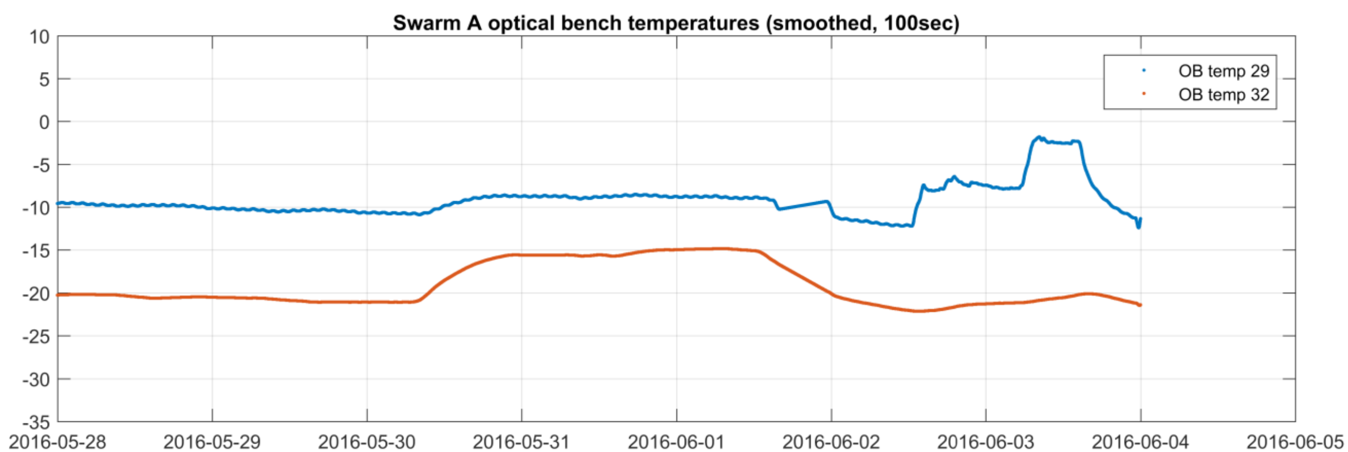
Time	Heater	Set-point [°C]	Comment
2016-05-30 07:21:28	21	-15	Heater predominantly on.
2016-05-31 13:03:20	21	-10	Heater not powerful enough to reach the set-point, i.e. heater constantly on
2016-06-01 12:24:48	21	-33	Nominal setting
2016-06-02 13:17:52	01	-9/-7	Set-point temperature quickly reached (less than 10 minutes), i.e. heater only on occassionally
2016-06-03 06:22:02	01	-4/-2	
2016-06-03 14:12:23	01	-30/-28	Nominal setting

Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)

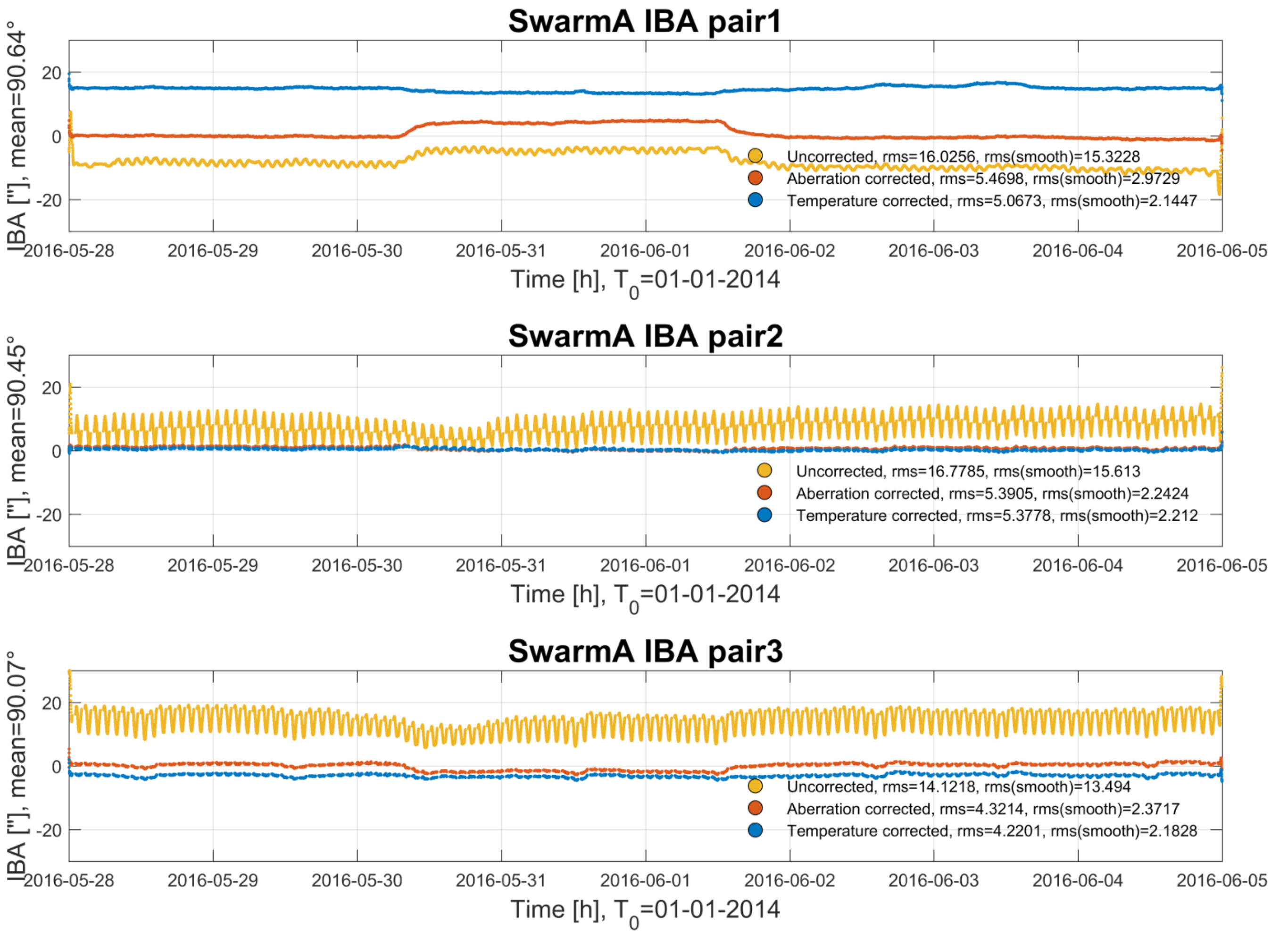


Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)

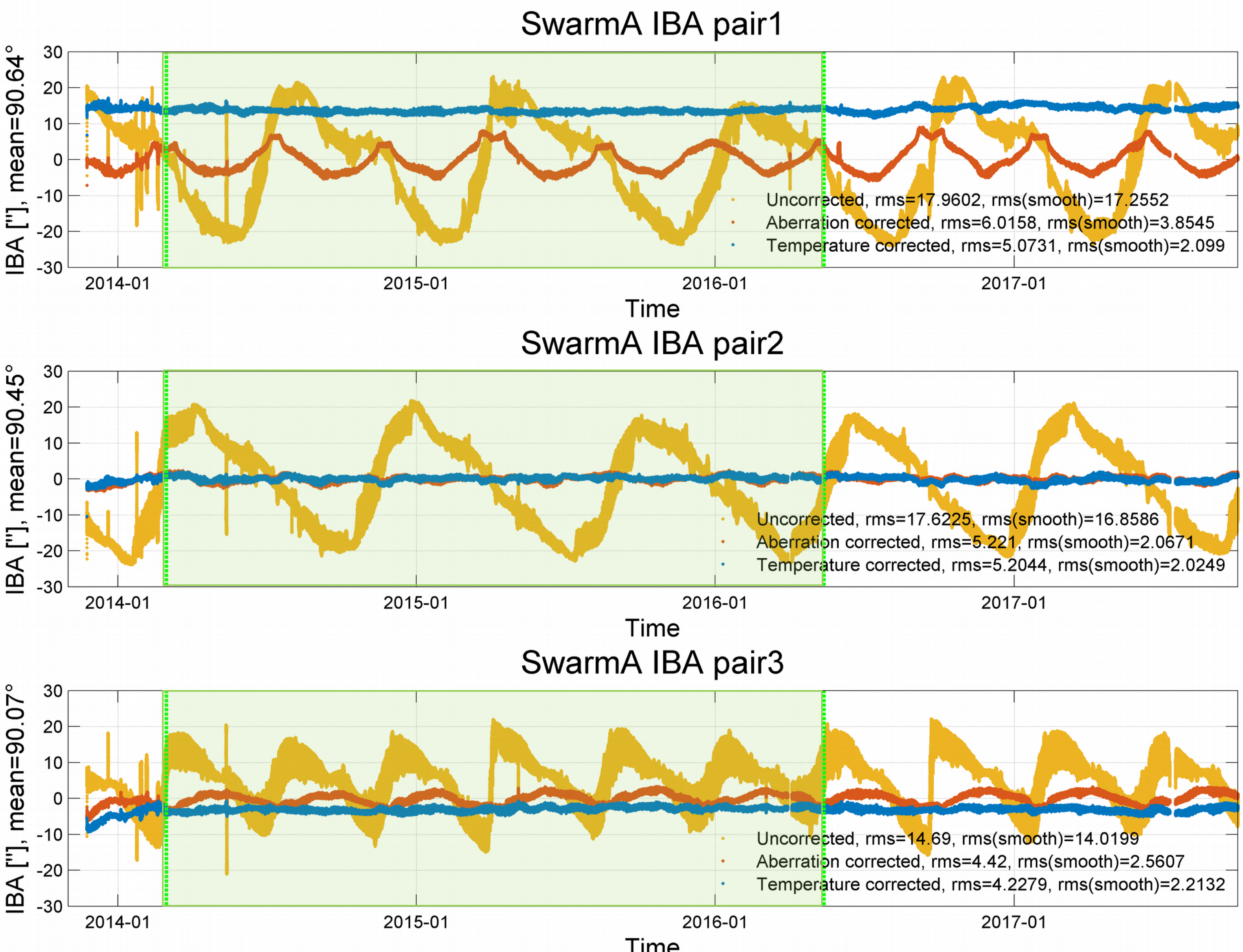




Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)



Correction effects Swarm A IBAs



Conclusion

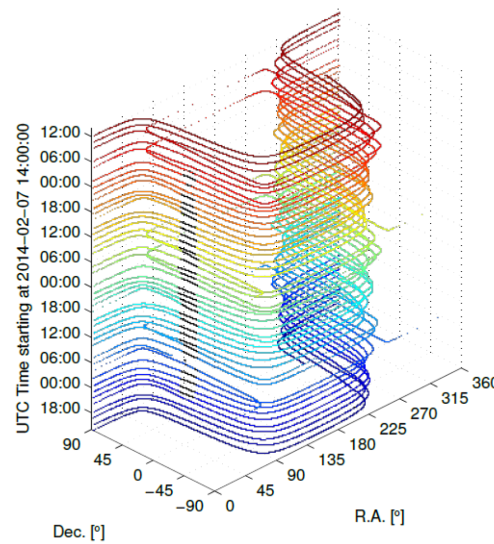
- µASC is performing as expected
- Inflight performance of the sensor baffle systems are better than designed
- After correction for the aberration effect, a small but still significant thermal signal remains in the IBA data
- The variation is found to correlate with temperatures and gradients measured at locations on the optical bench
- A model is computed for the correction of the thermo-elastic instabilities of the Swarm OB
- Corrected attitude data is very smooth and clean from any thermally induced phenomenon.
- Especially notable for the corrected data outside of the modelling period
- The technique shows an improvement in attitude determination that, after correction, meets the 2′′ requirements of Swarm satellite mission.
- Heater test: even though not tailored to this specific type of heat flow (where heat sources are heaters and not the Sun) behaves excellent and successfully removes the thermally induced OB instabilities

Backup slides

Star Tracker (STR):
Availability

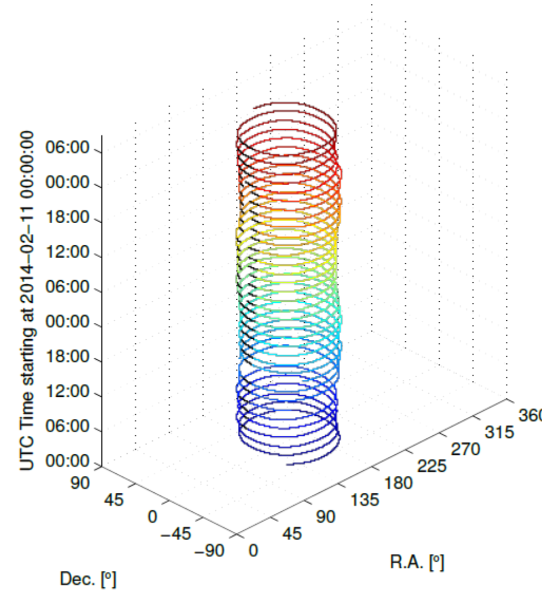
A Star Tracker must deliver valid updates when viewing nominal star fields, and exhibit graceful degradation when entering star fields with e.g. bright objects.

The Swarm STR system is designed to optimize attitude availability for the AOCS system also during times with the Sun and Moon entering the FoV of one of the sensors.



Validity percentage: 99.97%

# Valid CHUs	Counts	Percent
0	0	0.0000%
1	1	0.0004%
2	80258	31.3822%
3	175485	68.6174%

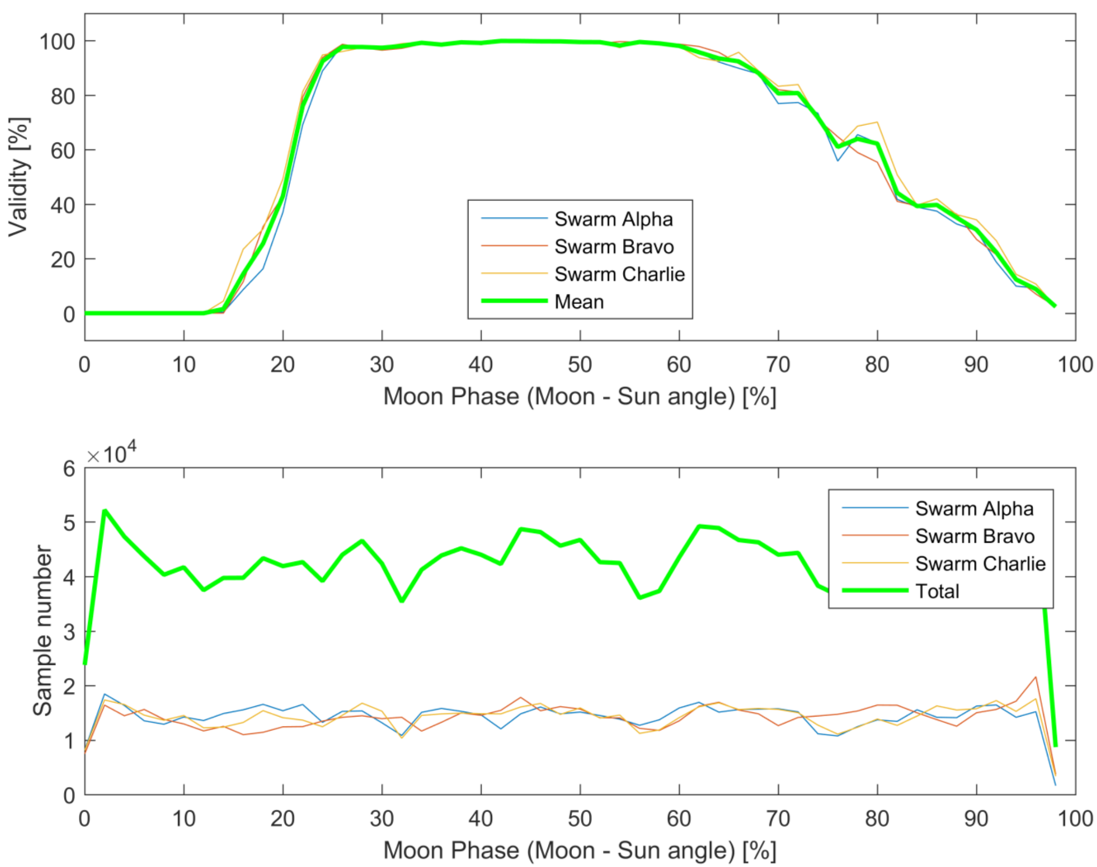


Validity percentage: 97.90%

# Valid CHUs	Counts	Percent
0	0	0.0000%
1	80	0.0423%
2	62567	33.0724%
3	126535	66.8853%

2-3 days of orbits showing a 50% phase Moon passage (left) and a 80% phase Moon passage (right). BBO flagged solutions are marked in black.

Effect of the moon phase on the SWARM ASC observation validity

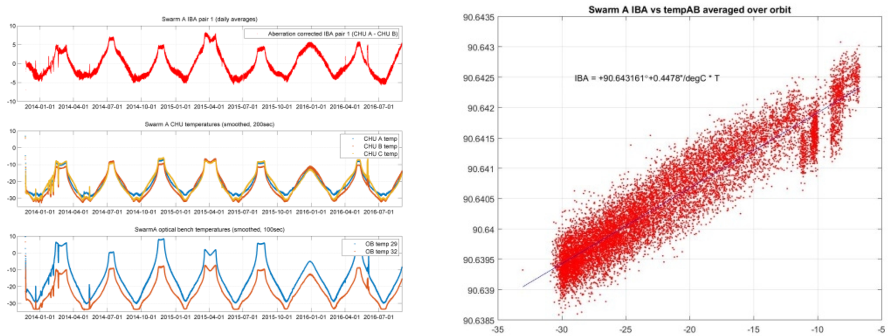


Star Tracker (STR):
Accuracy

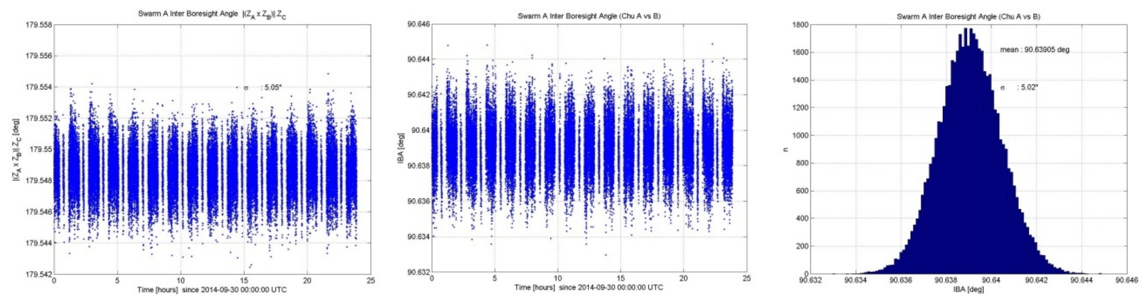
Accuracy of the Swarm STR system is best evaluated by comparing the attitude measurement of one sensor to the combined attitude from the other two.

The sensor platform stability may thus be determined from the angles between the sensor boresight, and by observing these angles as a function of time and temperatures

Similarly the measurement noise and error spectrum may be derived from the deviation of a single sensor solution from the triple sensor solution.



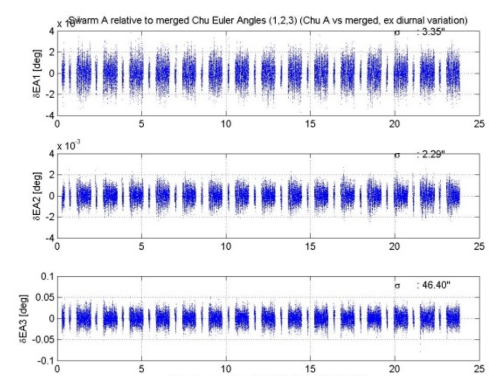
Stability of optical cube: Deep anomaly investigation…



Stability of optical cube diurnal: *Right, 3-CHU Z-axis stability. Middle, IBA CHUA vs CHUB. Left IBA AB histogram.*

1,2,3 Euler rotation

Performance of the individual CHU:
CHU-A compared to the merged solution.



3.25"

2.29"

Star Tracker (STR):
BBO flag

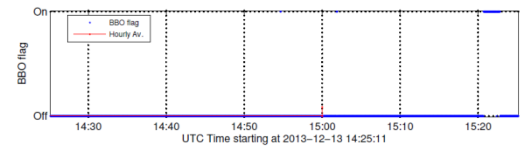
A Star Tracker attitude measurement may be disturbed, if a bright object enters the FoV.

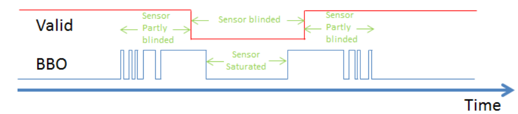
Therefore, the Swarm STR has implemented a flag that alerts the user if an unexpected bright object enters the FoV, or has dubbed the Big Bright Object or BBO flag.

Since launch, the STR systems on all three Swarm satellites have experienced unexpected triggering of the BBO flags at certain times.

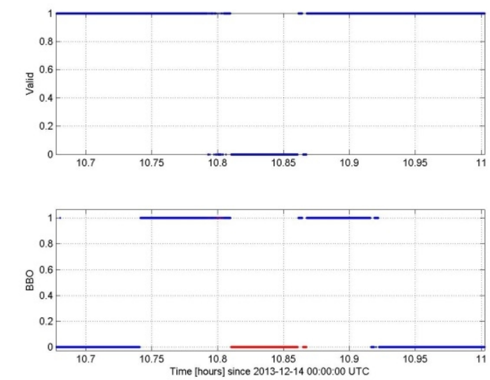
Images acquired at these times have revealed unexpected objects orbiting close to the Swarm constellation.

Sporadic triggering of BBO: *Swarm A, CHU A, 2013 13 Dec. 14:55:10 UT, BBO time line and acquired image*





Central Moon passage: *Swarm A, CHU C, 2013 14 Dec. 89% Moon*



Spo
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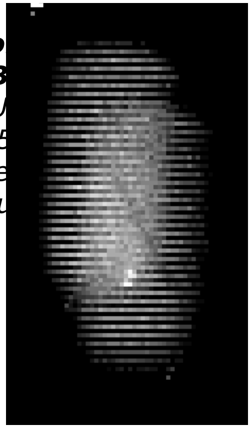
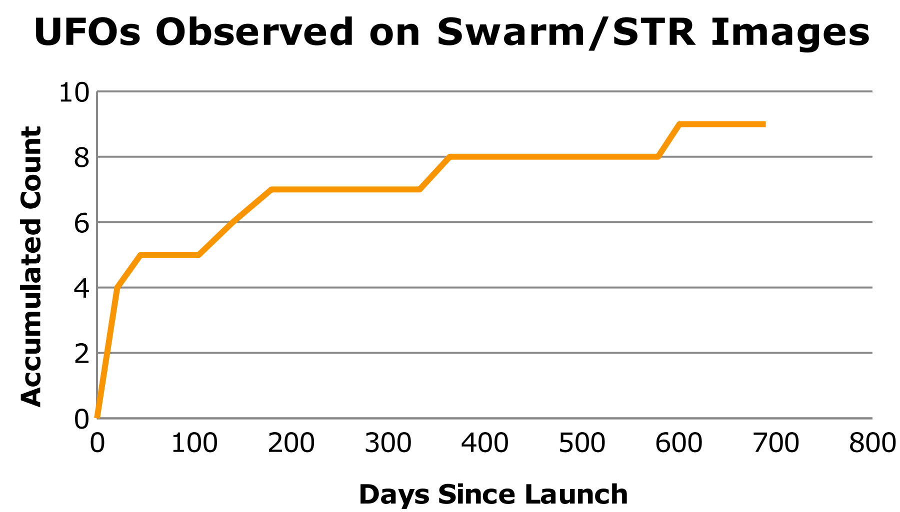
CHU
14:5
time
acqu



Zoomed view

Star Tracker (STR):
BBO flag

Month	Count	Month	Count
2013 - Dec	4	2015 - Nov	0
2014 - Jan	1	2015 - Dec	0
2014 - Feb	0	2016 - Jan	0
2014 - Mar	0	2016 - Feb	0
2014 - Apr	1	2016 - Mar	0
2014 - May	1	2016 - Apr	0
2014 - June	0	2016 – May	0
2014 - July	0	2016 – Jun	0
2014 - Aug	0	2016 – Jul	0
2014 - Sep	0	2016 – Aug	0
2014 - Oct	0	2016 – Sep	0
2014 - Nov	1	2016 - Oct	0
2014 - Dec	0	2016 – Nov	0
2015 - Jan	0	2016 – Dec	0
2015 - Feb	0	2017 – Jan	0
2015 - Mar	0	2017 – Feb	0
2015 - Apr	0	2017 – Mar	0
2015 - May	0	2017 – Apr	0
2015 - Jun	0		
2015 - July	1		



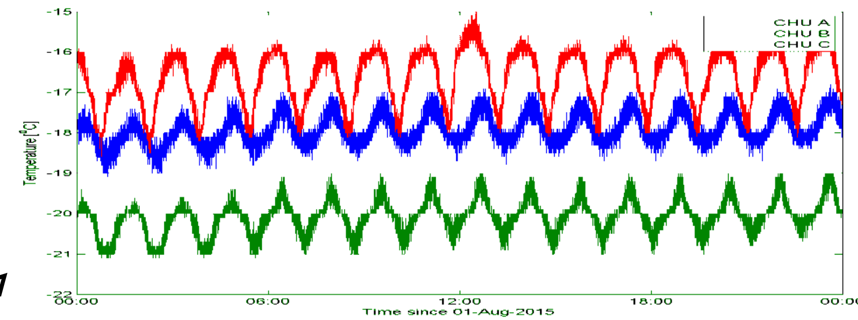
Star Tracker (STR):
Thermal stability

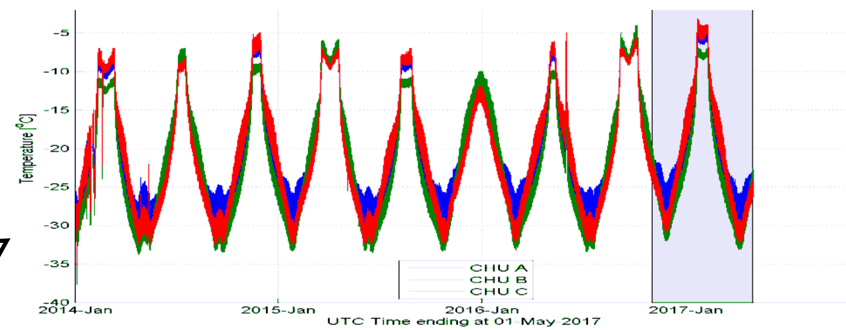
Data 2014/01/01 to 2016/10/31

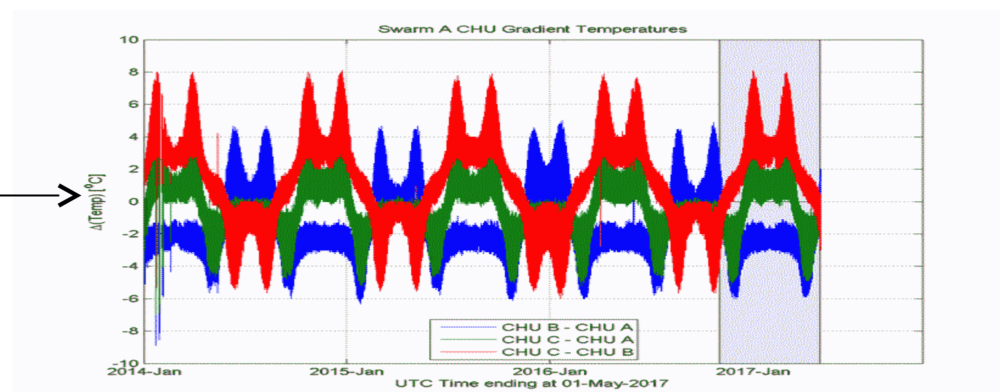
Star Trackers thermal stability is a significant parameter for performance, and thorough thermal design in form of Optical bench, heat pipes, radiator and baffle finished has been implemented.

Plots to the right show the CCD temperature evolution for the three CHUs:

- In-orbital variation
- Long term temperature stability
- Long term temperature gradient between CHus

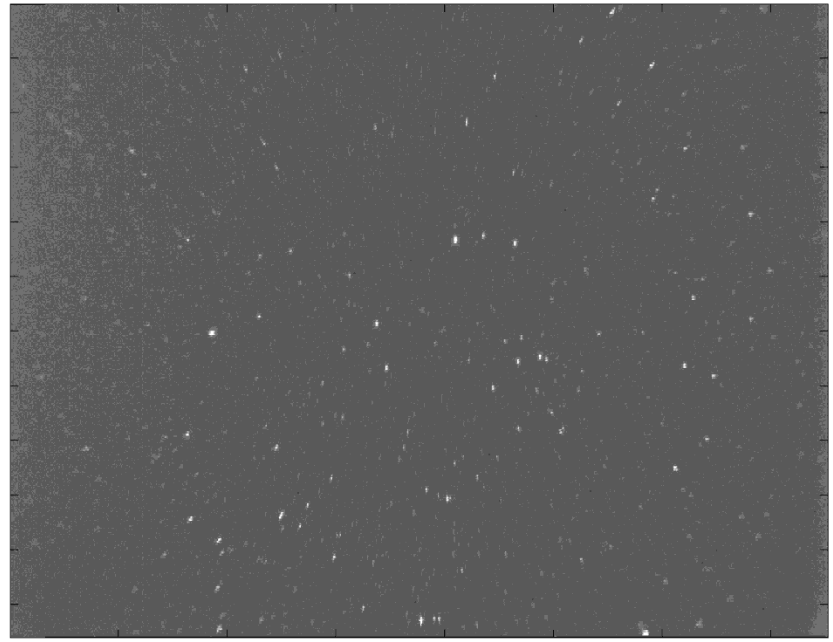






Star Tracker (STR): Instrument Aging

- The only relevant instrument aging effect is hotspot accumulation on the CCD.
- In order to keep track of this effect, uncompressed images are downloaded from each of the CHUs at monthly basis.
- The hotspot count is defined as the number of image hotspots with intensities peaking above 20 digital levels relative to the image background.
- The instrument performance will start degrading when more than 5000 such hotspots are present within one image frame.
- Due to the very low operational temperature of the Swarm CHUs, only a negligible hotspot accumulation is foreseen over the mission lifetime.



Example of downloaded image (contrast increased to emphasize details)

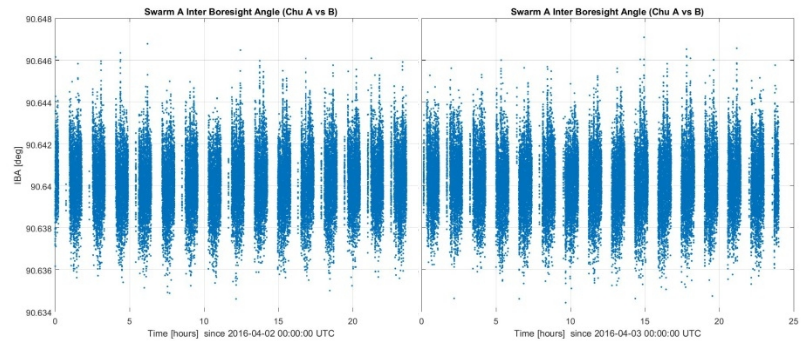
Images for aging study are captured April 15, 2016

Spacecraft	CHU	Timestamp of Acquisition [s]	Number of hotspots	Status
SwA 514044010	CHU-A (SW-C001-C2)	514041010	<10	Healthy
	CHU-B (SW-C001-C3)	514050010	<5	Healthy
SwB 514043410 514050010	CHU-A (SW-C001-C8)	514038010	<10	Healthy

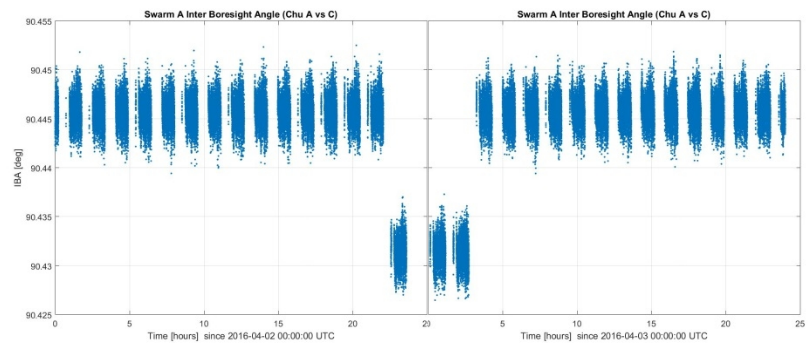
Star Tracker (STR):
IBA Anomaly on 2016-093 to 094

During approximately 6 hours between 2016-093 and 094 and unexpected variation in the IBA for CHU pairs A-C and B-C is observed for Swarm A. Pair A-B is not affected.

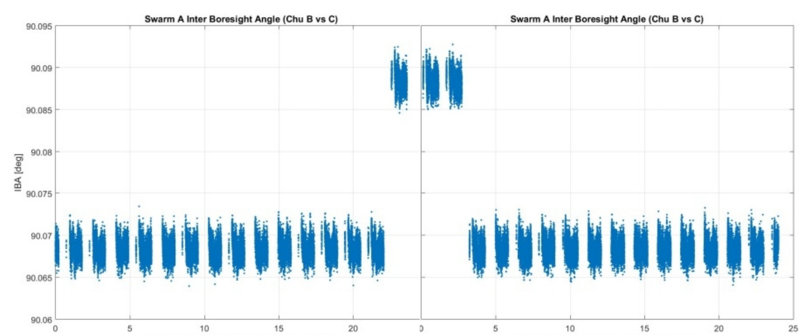
The effect occurs while CHU C is centrally blinded by the Sun



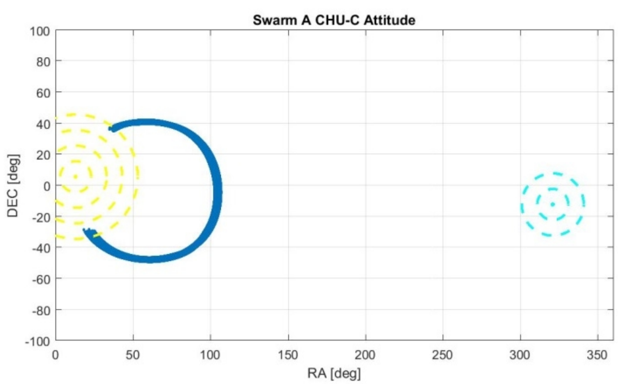
IBA (A-B)



IBA (A-C)



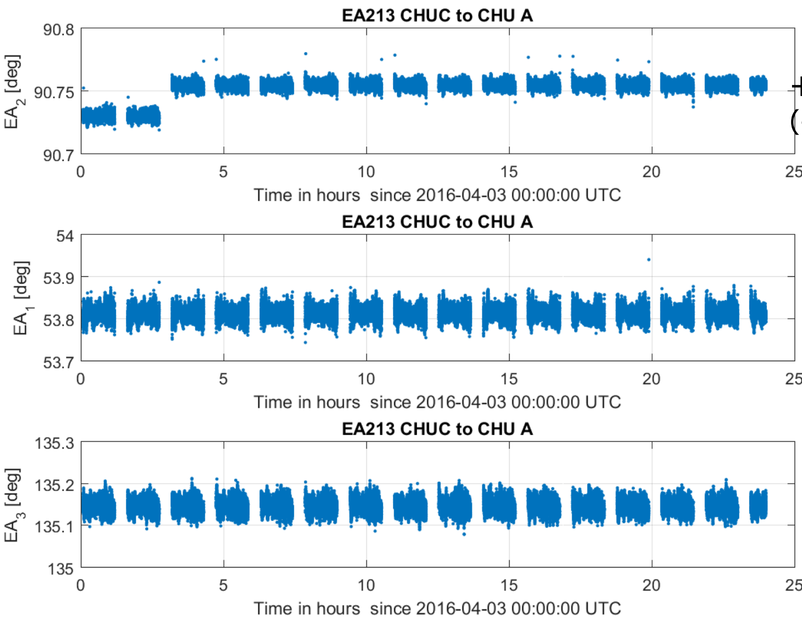
IBA (B-C)



Star Tracker (STR):
IBA Anomaly on 2016-093 to 094

Expressing the full inter CHU orientation as 2-1-3 euler angles from CHU-C to the other CHU (A, B):

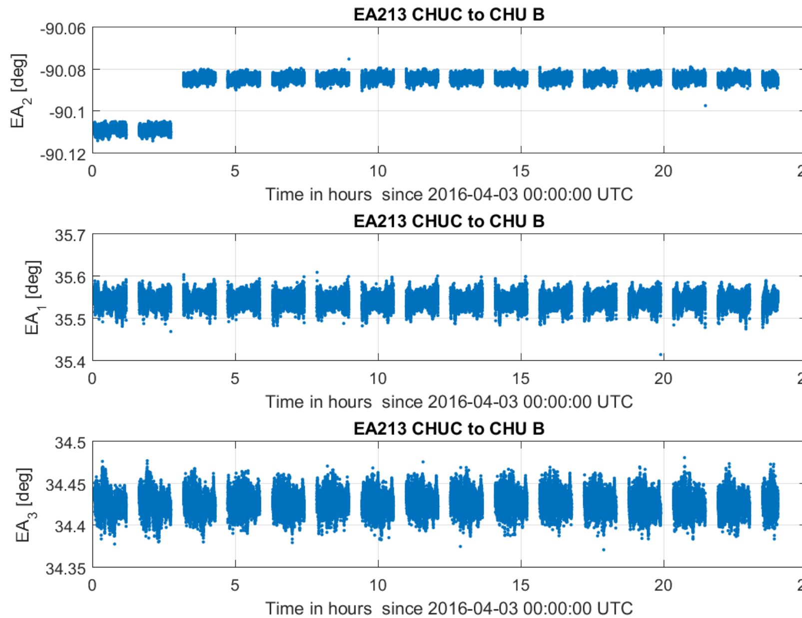
Effect corresponds to a rotation of CHU-C about its Y axis by ~ +88″



+87.9″
(σ~9″)

-6.5″
(σ~50″)

-0.6″
(σ~50″)



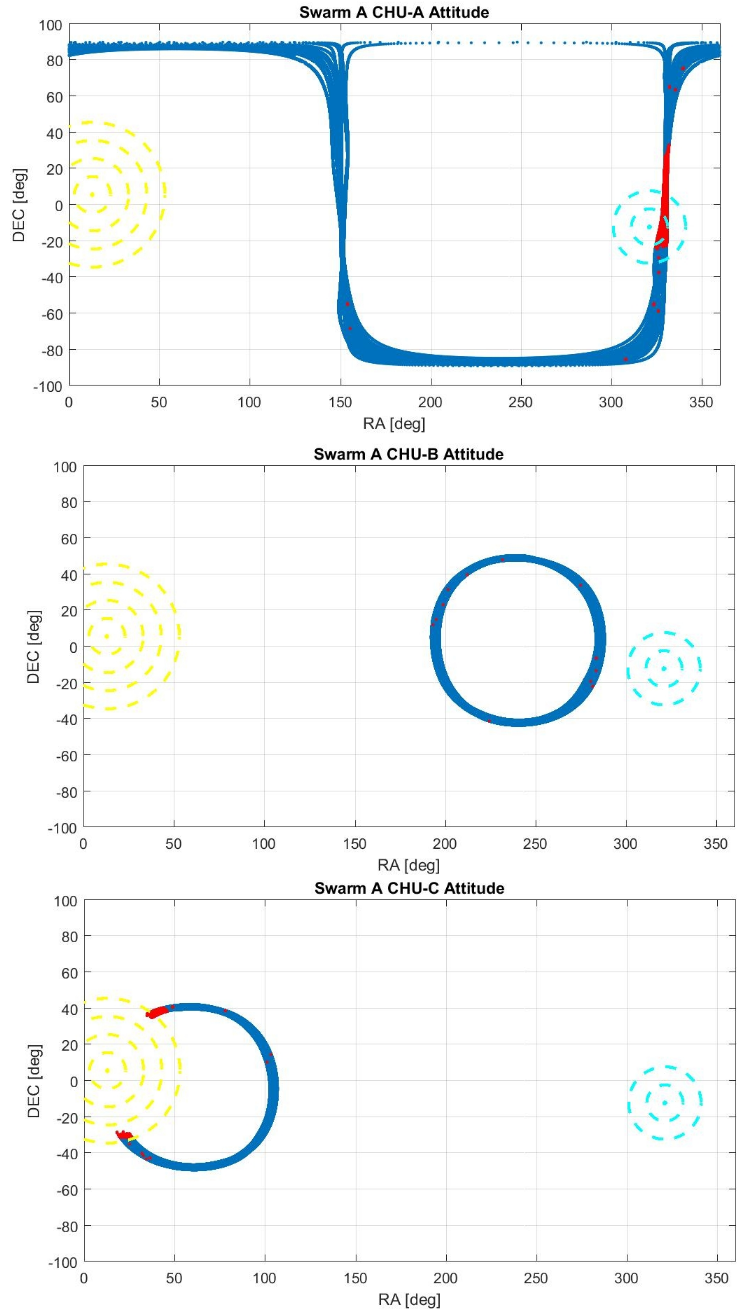
+88.9″
(σ~5″)

+7.0″
(σ~50″)

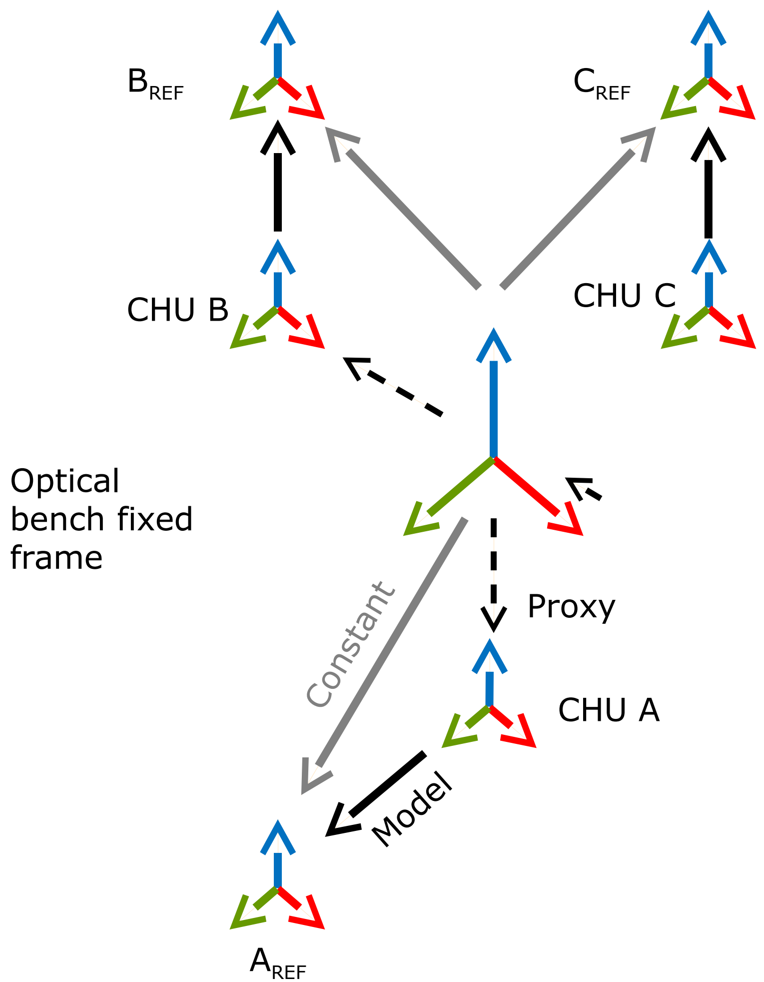
+2.0″
(σ~45″)

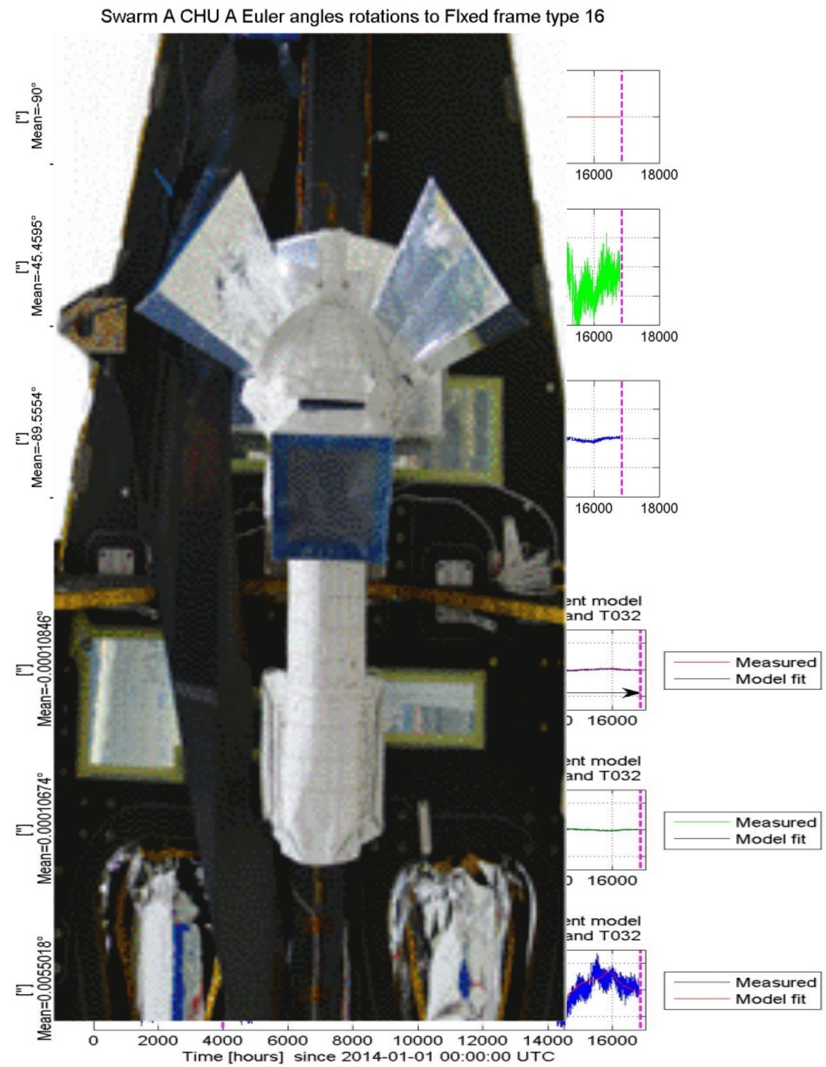
Backup slide: CHU LOS 2016-093

- Shown is also Sun and Moon

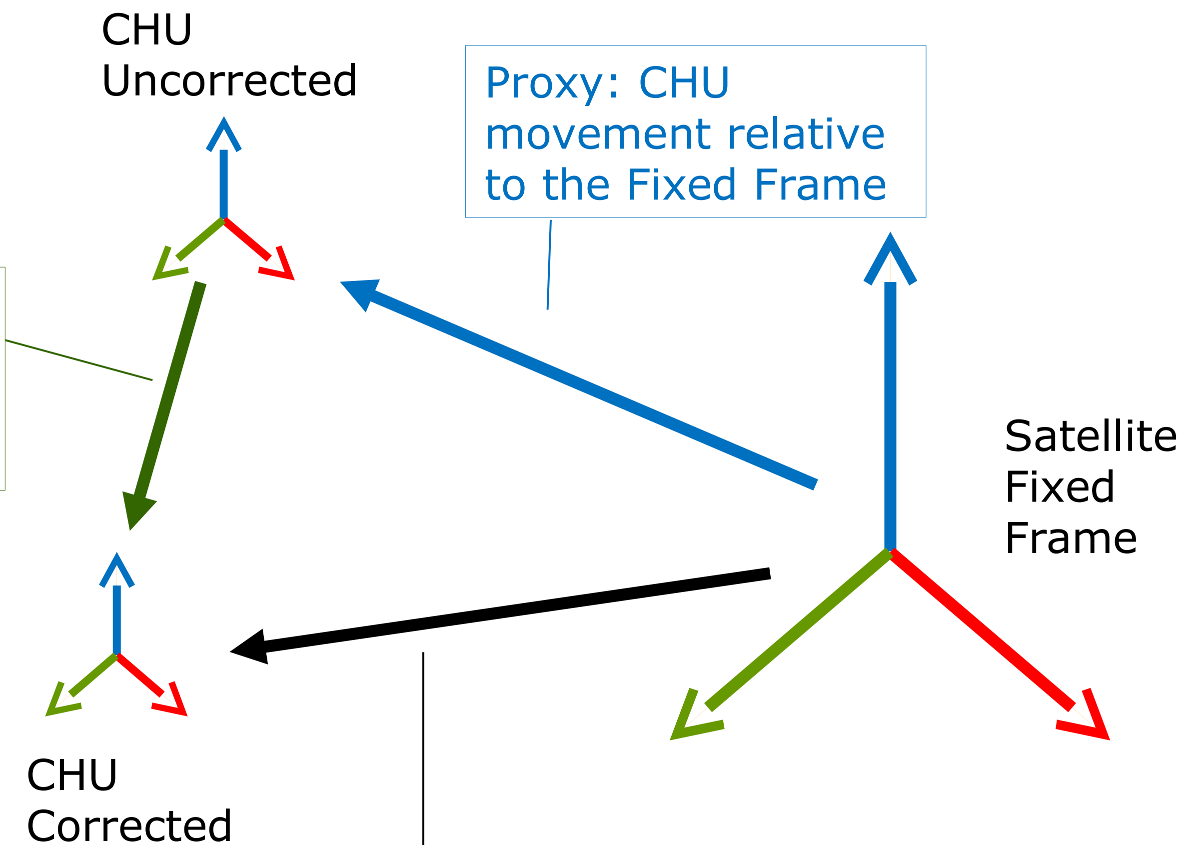


Swarm thermal correction model: An overview



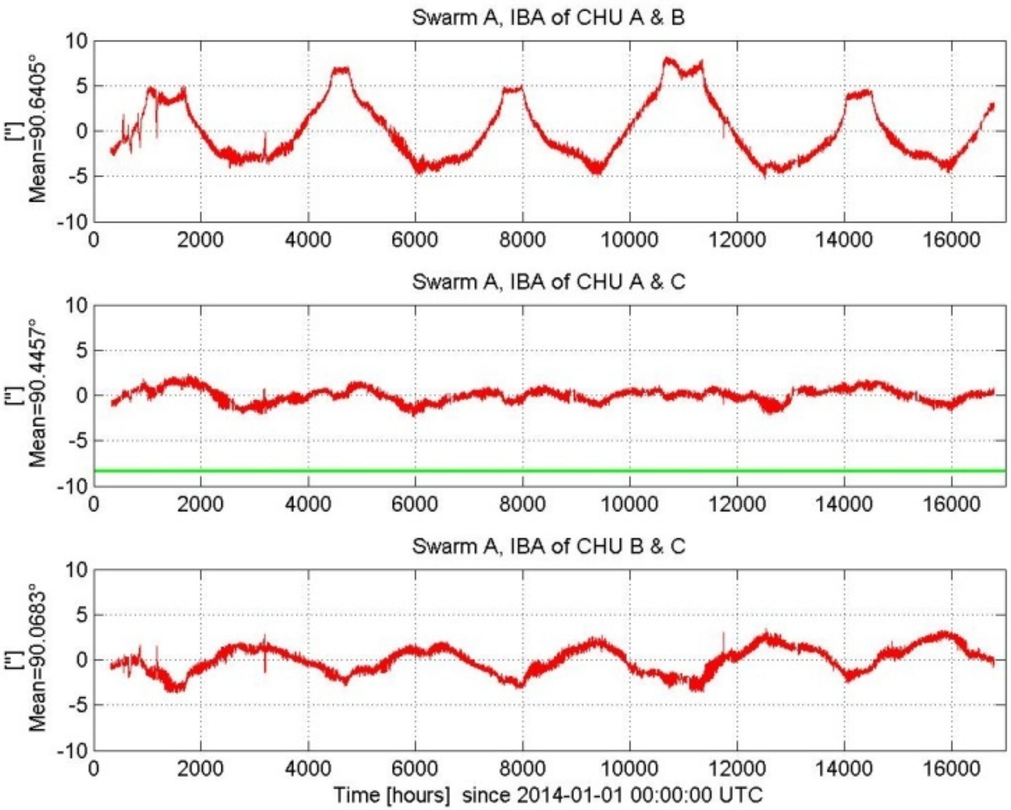


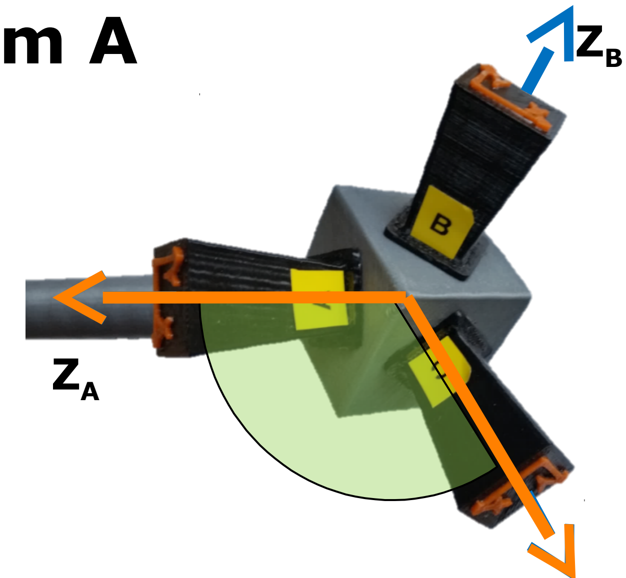
Swarm A Model

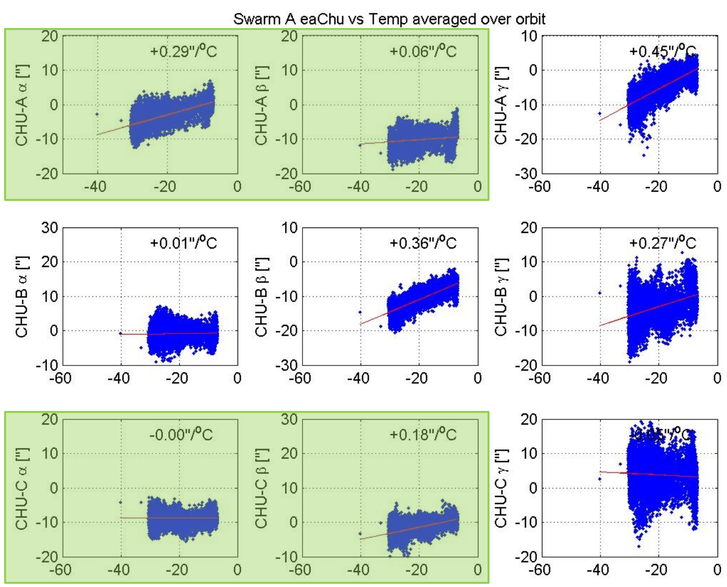


Tcal [°C]	T1 (CHU)	T2,T3 (OB)
Sw-A	+4.0	0.0
Sw-B	+13.0	+9.0
Sw-C	+13.5	+9.5

Fixed frame construction Swarm A





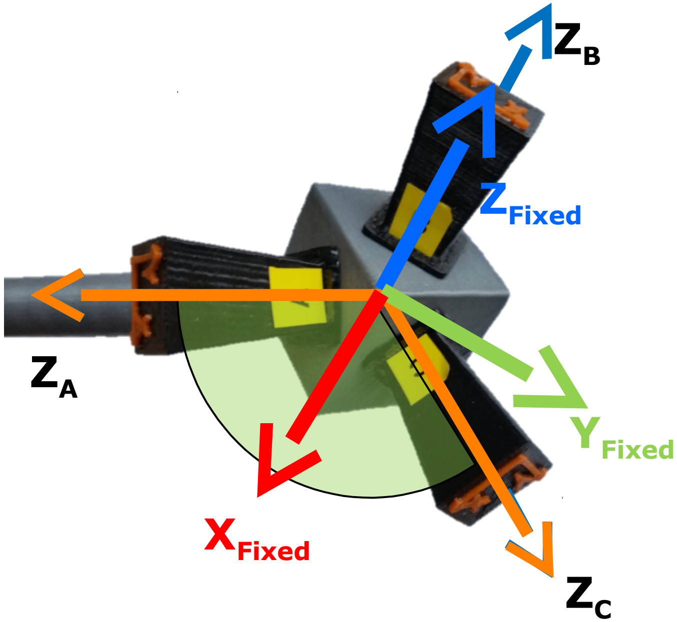


Swarm correction application: Fixed frame construction

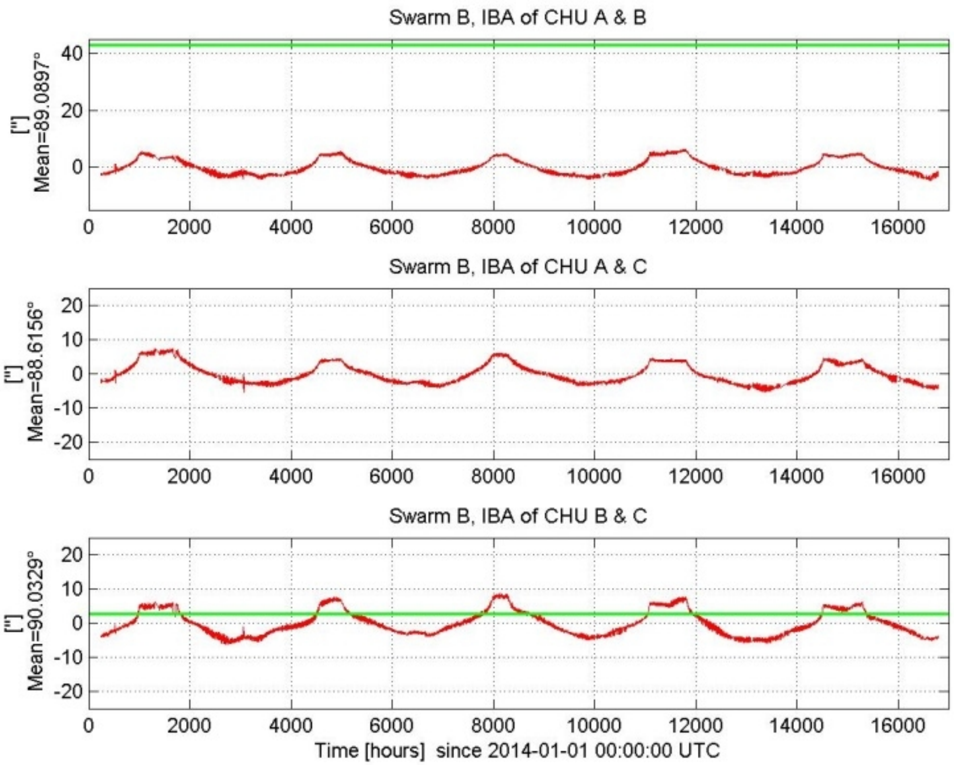
$$Z_F = \frac{Z_A \times Z_C}{|Z_A \times Z_C|}$$

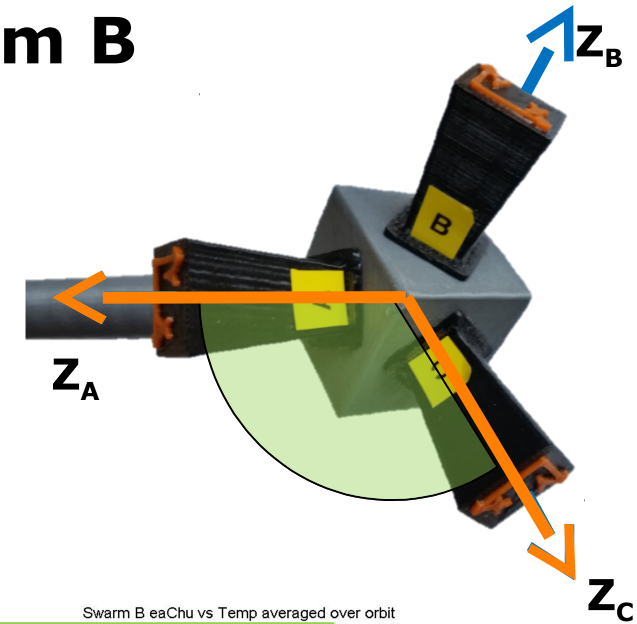
$$X_F = \frac{Z_A + Z_C}{|Z_A + Z_C|}$$

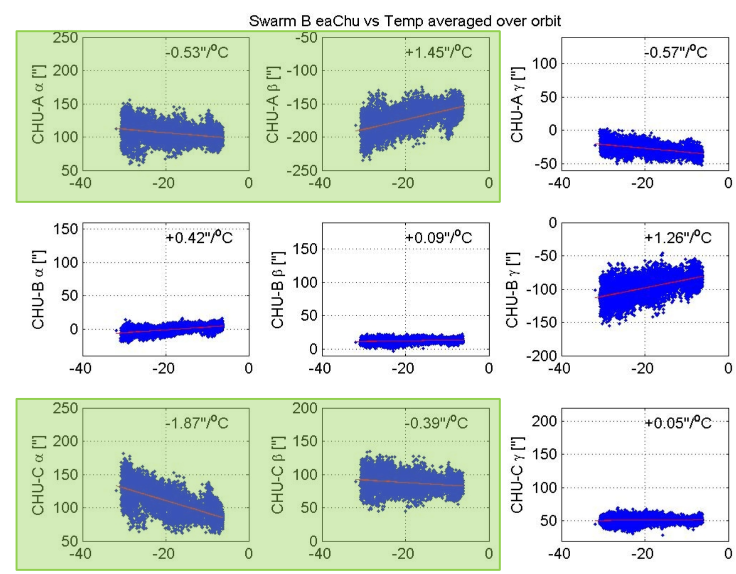
$$Y_F = \frac{Z_F \times X_F}{|Z_F \times X_F|}$$



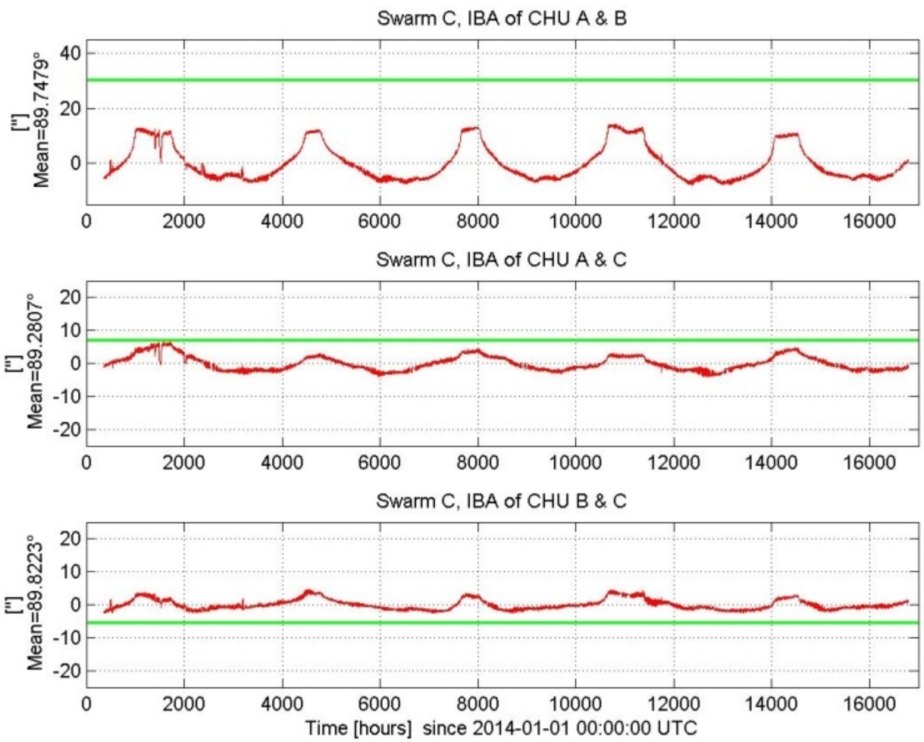
Swarm correction application: Fixed frame construction Swarm B

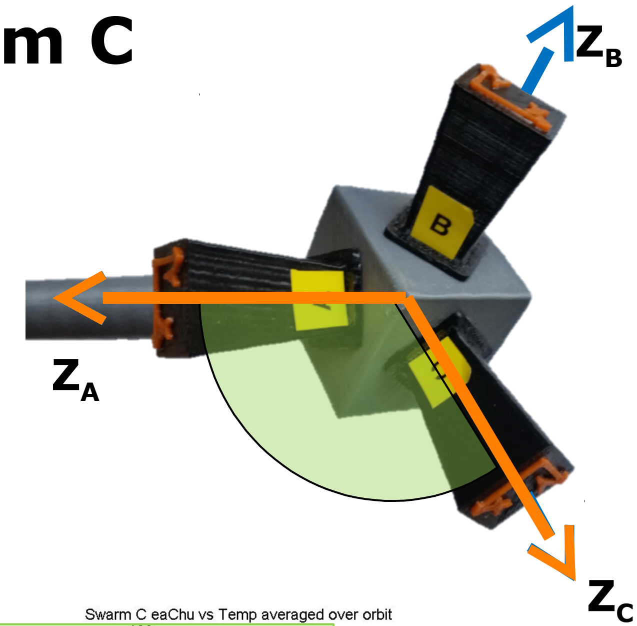


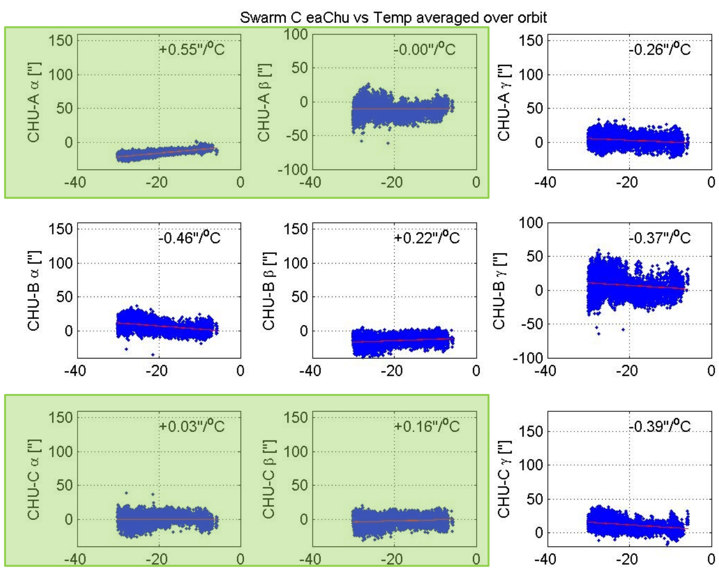




Swarm correction application: Fixed frame construction Swarm C







Applying temperature Correction

- Using CHU (A, B and C) temperatures and Optical Bench (T_{029} and T_{032}) temperature

- Omitting days where house keeping or optical bench data is missing

- Concatenate a day before and after for interpolation and smoothing

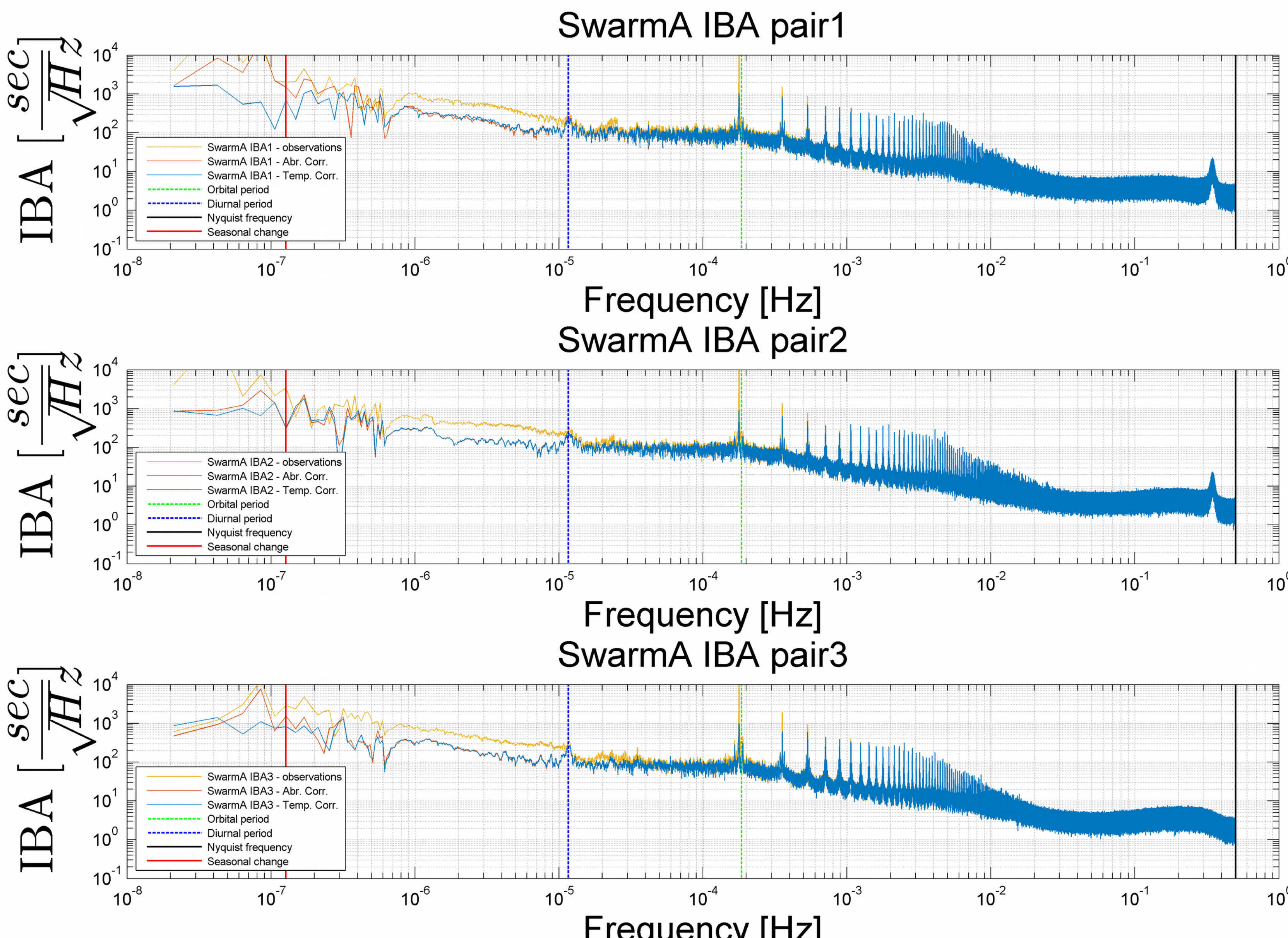
$$\begin{bmatrix} T_{chuA(day-1)} \\ T_{chuA(day)} \\ T_{chuA(day+1)} \end{bmatrix} \quad \begin{bmatrix} T_{029(day-1)} \\ T_{029(day)} \\ T_{029A(day+1)} \end{bmatrix} \quad \begin{bmatrix} T_{032(day-1)} \\ T_{032(day)} \\ T_{032(day+1)} \end{bmatrix}$$

- Remove outliers in House Keeping Temperatures (T<-35)

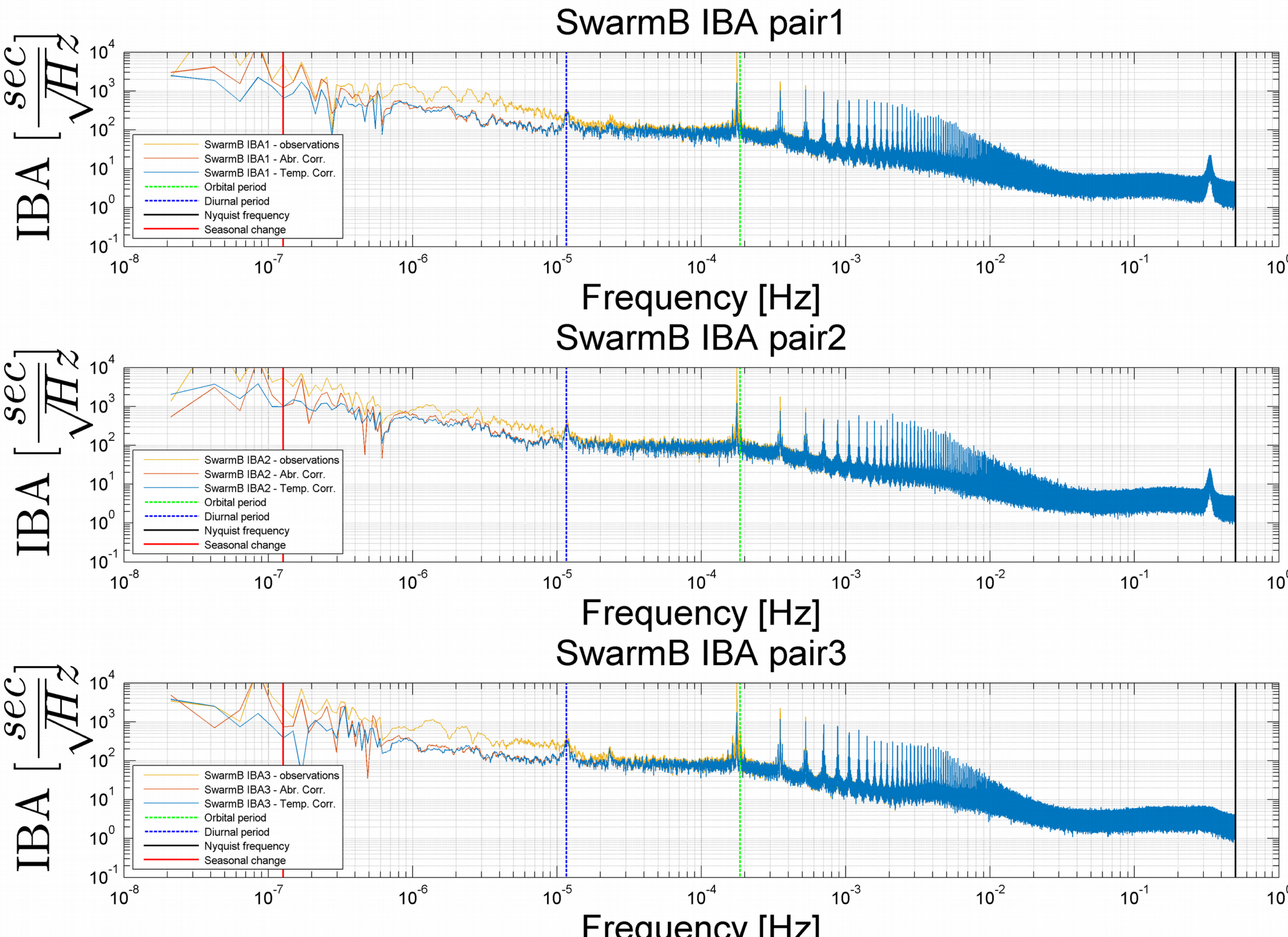
- Smooth temperatures with moving average filter of 400 sec width

- Interpolate temperature on attitude times
  (Extrapolation: Assign last value for points outside the domain)

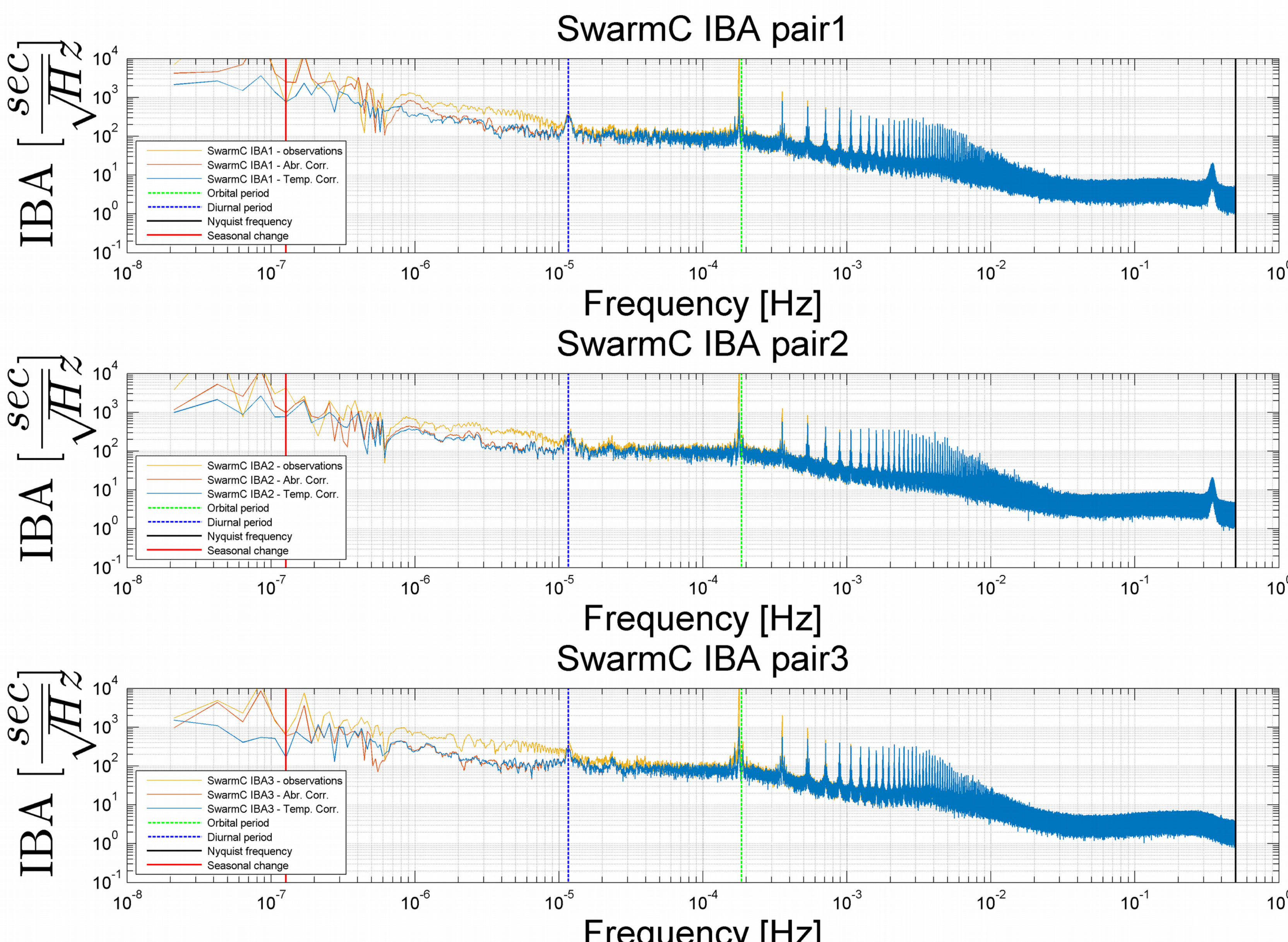
Correction effects Swarm A IBAs



Correction effects Swarm B IBAs



Correction effects Swarm C IBAs



Correction effects RMS (smooth 200sec)

IBA 1	Swarm A	Swarm B	Swarm C
Original	17.1274	17.2359	17.8612
Abr. Corr.	3.6793	3.6951	6.4938
Temp. Corr	2.0658	2.6369	2.5738

IBA 2	Swarm A	Swarm B	Swarm C
Original	16.9776	17.6000	17.2446
Abr. Corr.	2.1078	3.5595	2.9496
Temp. Corr	2.0246	2.3968	2.2766

IBA 3	Swarm A	Swarm B	Swarm C
Original	14.3597	14.7681	14.4139
Abr. Corr.	2.5340	4.3181	2.5876
Temp. Corr	2.2595	2.6406	2.1923