Correction model for the thermo-elastic instability of SWARM optical bench

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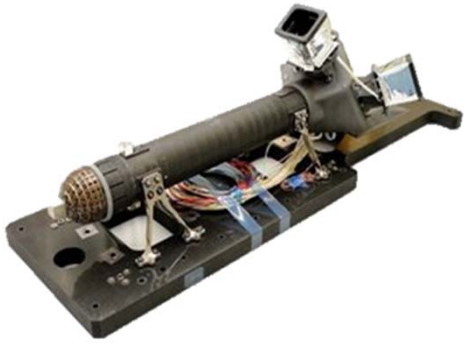


DTU Space
National Space Institute

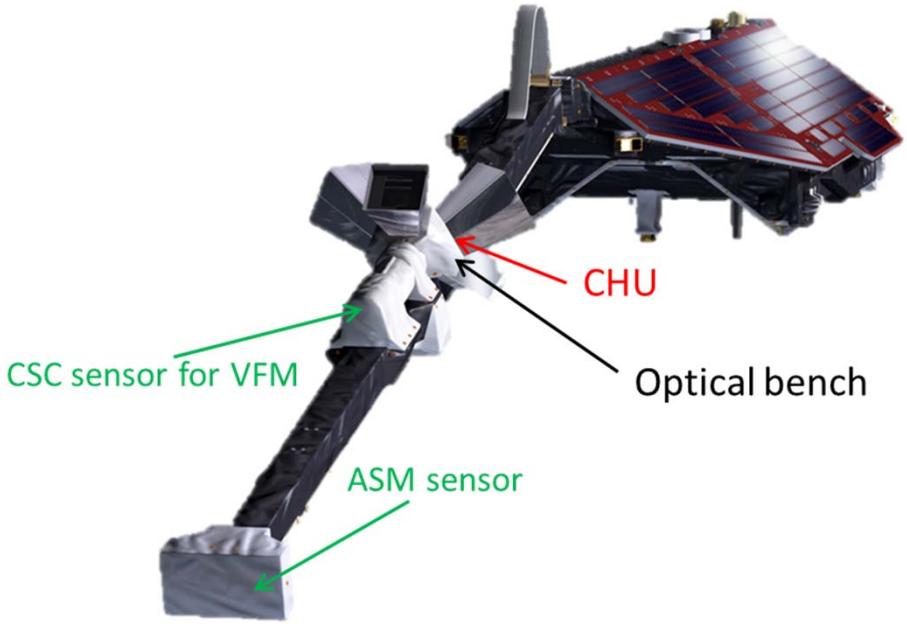
µASC Star Tracker

- 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.

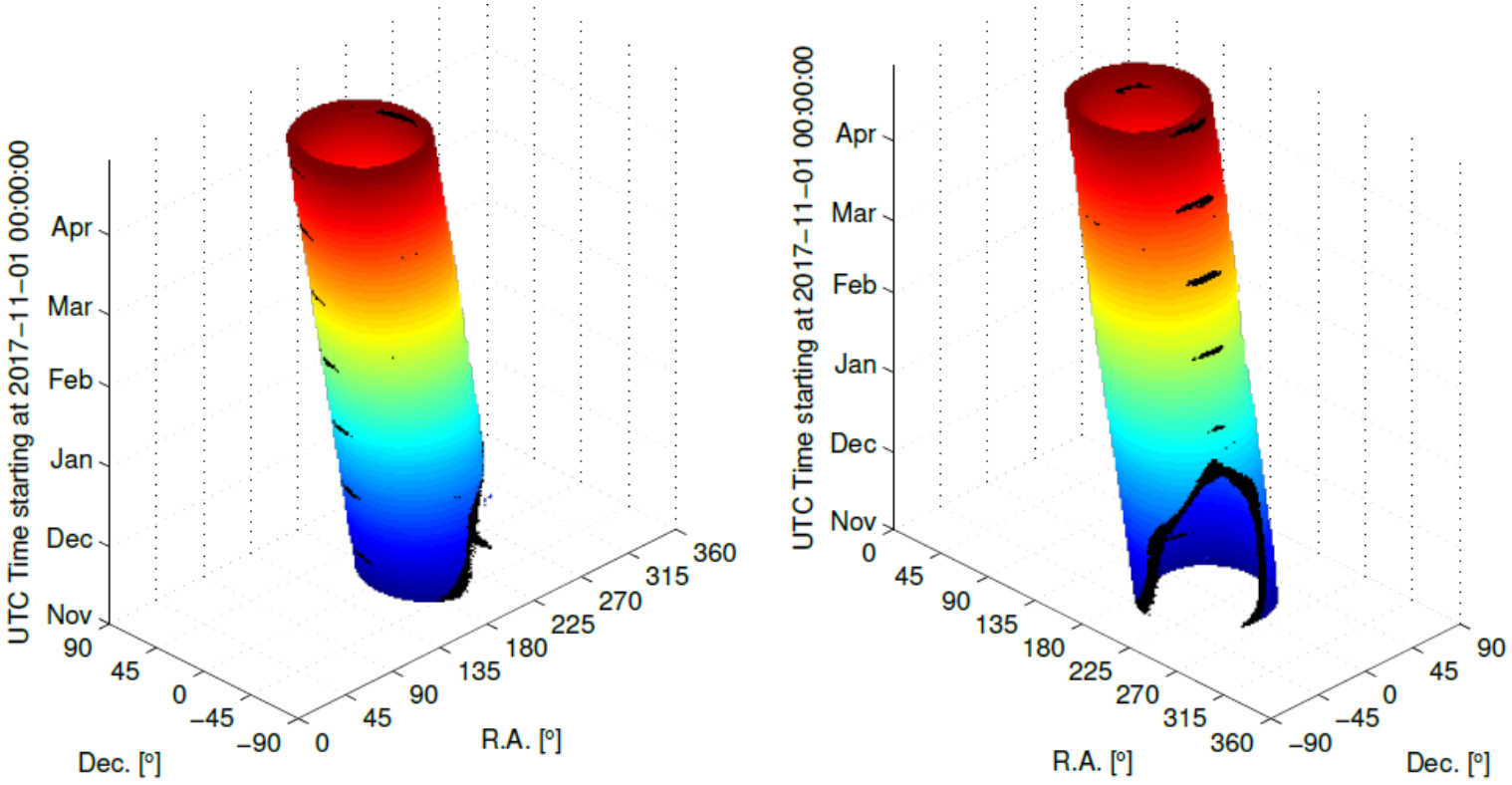
- objective of VFM is to measure the magnetic field vector



Star Tracker (STR) – Performance

Availability

Data 2017/11/01 to 2018/05/01

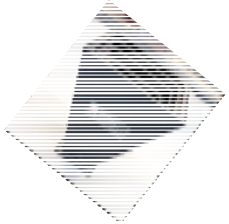


Right Ascension and Declination for Swarm A, CHU C over time. Black attitudes indicate BBO flags.

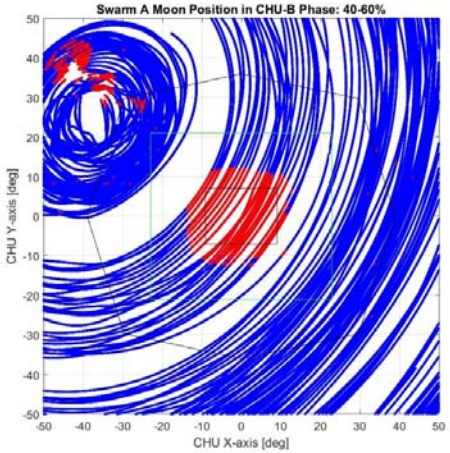
Star Tracker (STR):
Availability of 2 or 3 sensor solutions

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.

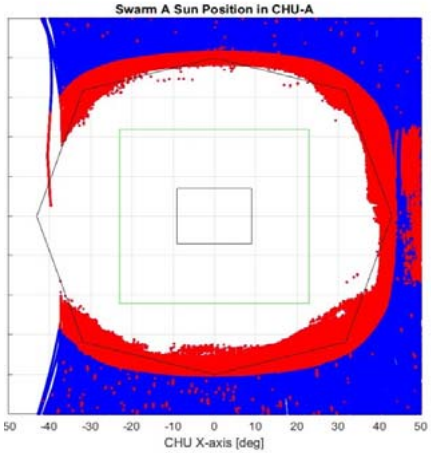
- Inflight performance of the sensor baffle systems are better than designed
- Inflight performance towards a 50% Moon show full resilience



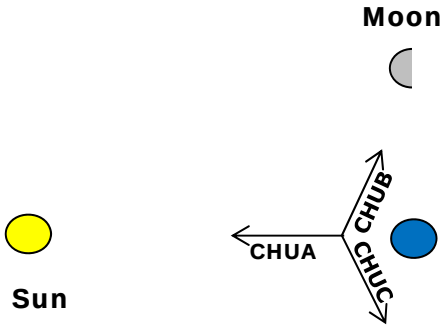
Demonstrating that 2 or 3 sensor solutions are granted, with excellent margins, for the planned mission profile.



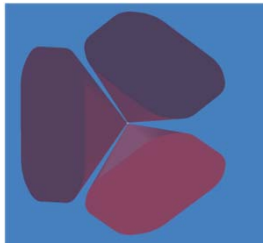
Operations vs Moon:
Position of 40-60% Moon in Swarm A CHU-B, Valid attitudes, with BBO flag(red), 184 days data



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



Swarm in orbit around Earth



Baffle performance: Swarm Sun Exclusion cones

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 also during times with the Sun and Moon entering the FoV of one of the sensors.

Concurrent valid attitudes from all CHUs:
2017/11/01 to 2018/05/01

Swarm A

# Valid CHUs	Counts	Percent
0	0	0.0000%
1	3269	0.0210%
2	5027912	32.3297%
3	10520818	67.6493%

Validity percentage: **100.00%**

Swarm B

# Valid CHUs	Counts	Percent
0	1	0.0000%
1	12751	0.0820%
2	4880251	31.3804%
3	10658926	68.5376%

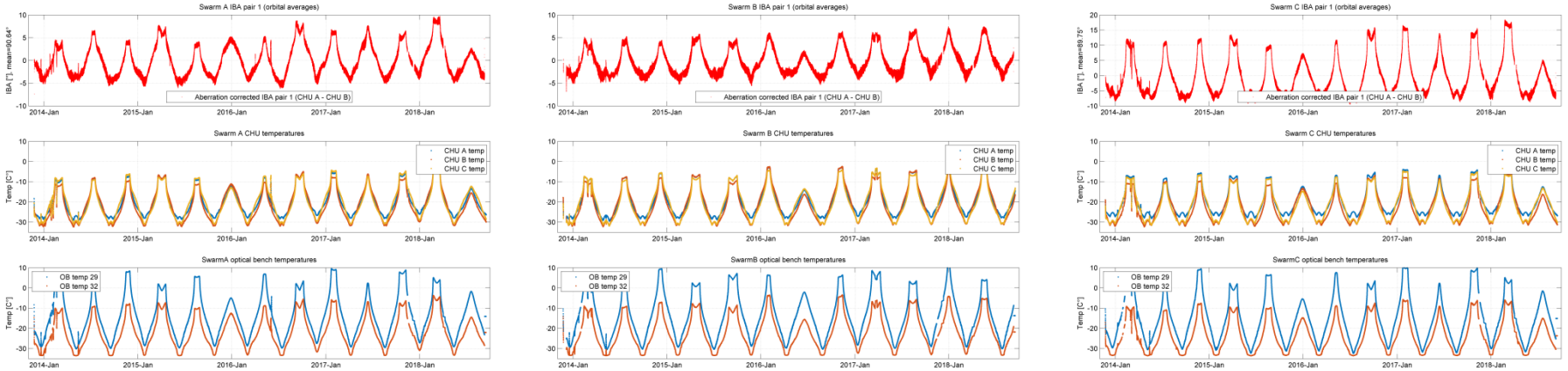
Validity percentage: **100.00%**

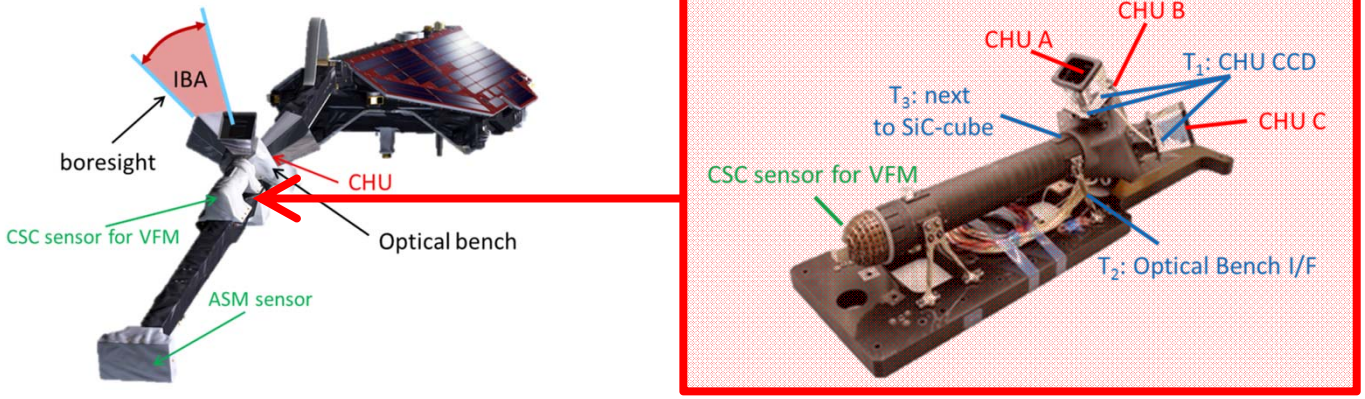
Swarm C

# Valid CHUs	Counts	Percent
0	2	0.0000%
1	3349	0.0215%
2	5080718	32.6693%
3	10467919	67.3092%

Validity percentage: **100.00%**

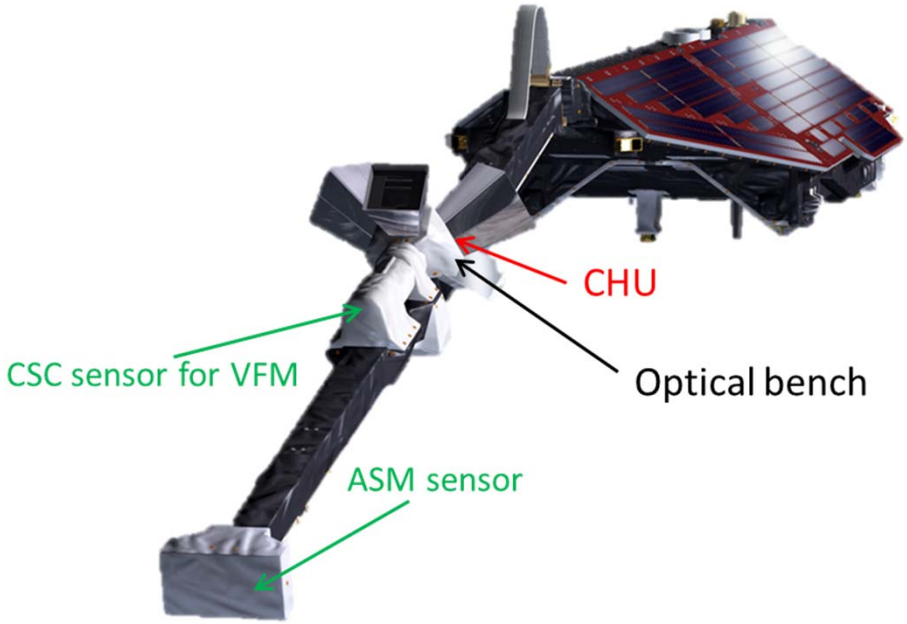
Correlation of the Inter-boresight angles (IBA) with temperatures





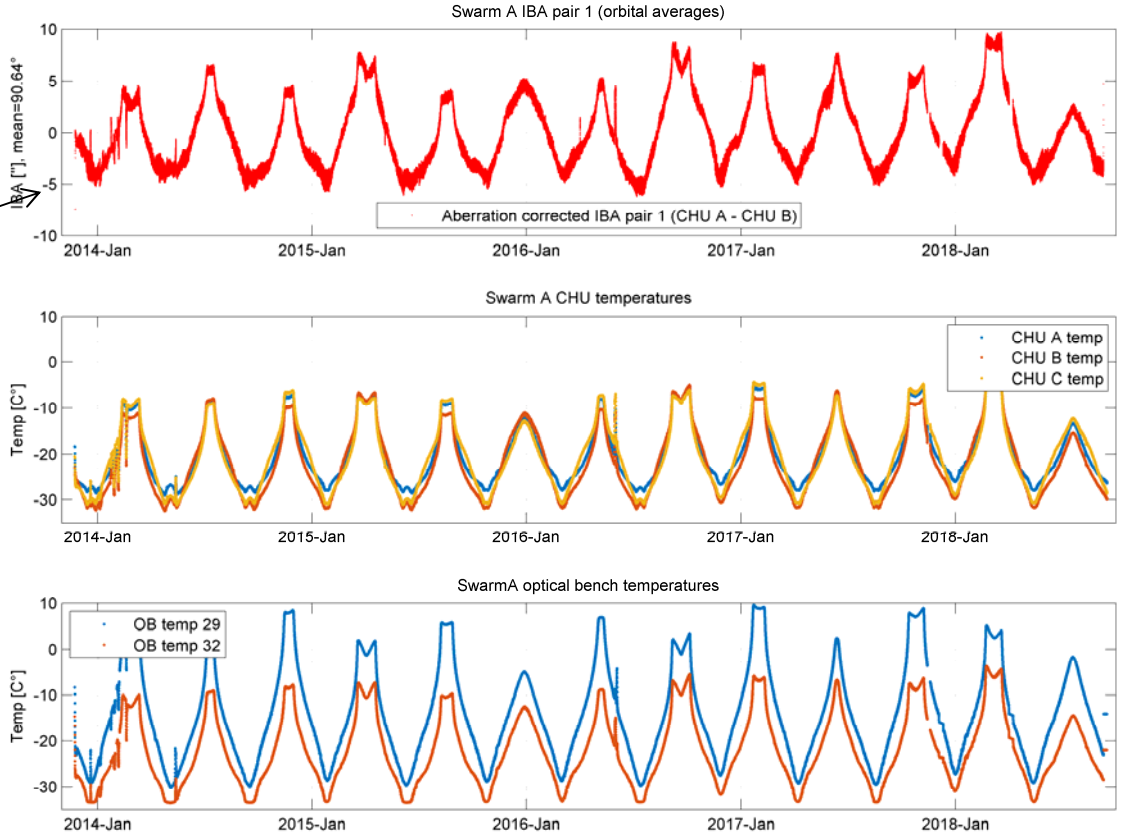
Swarm satellite

- 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)



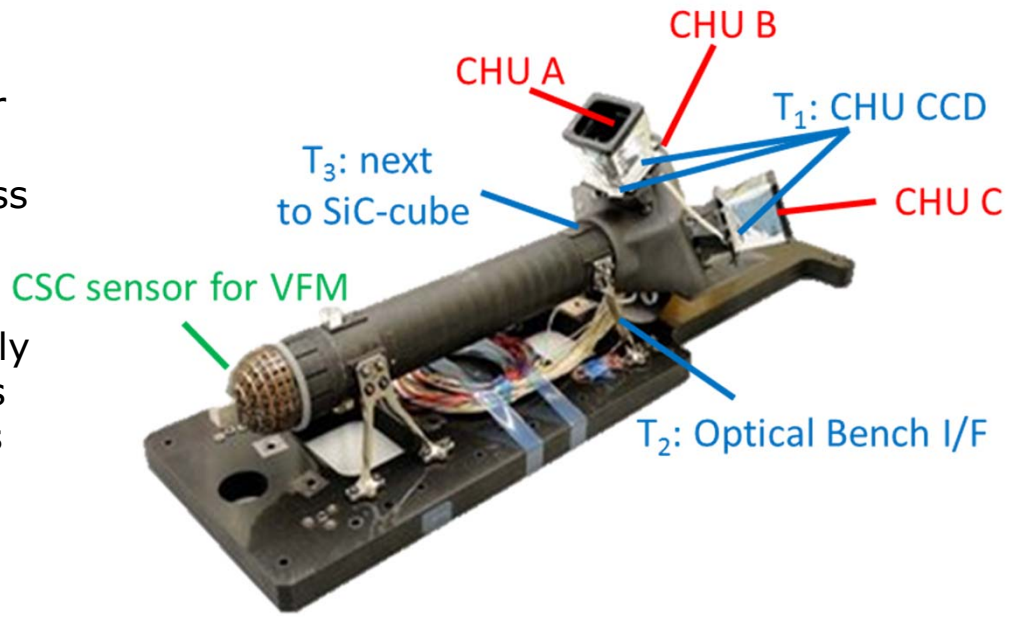
Swarm A: IBA and temperatures

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

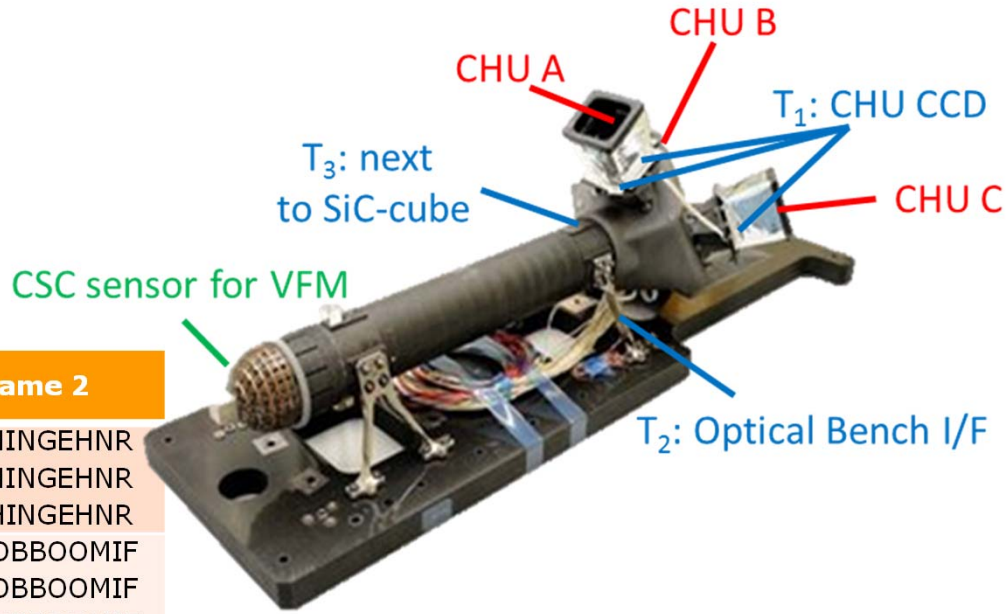


Swarm Optical Bench (OB)

- 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).

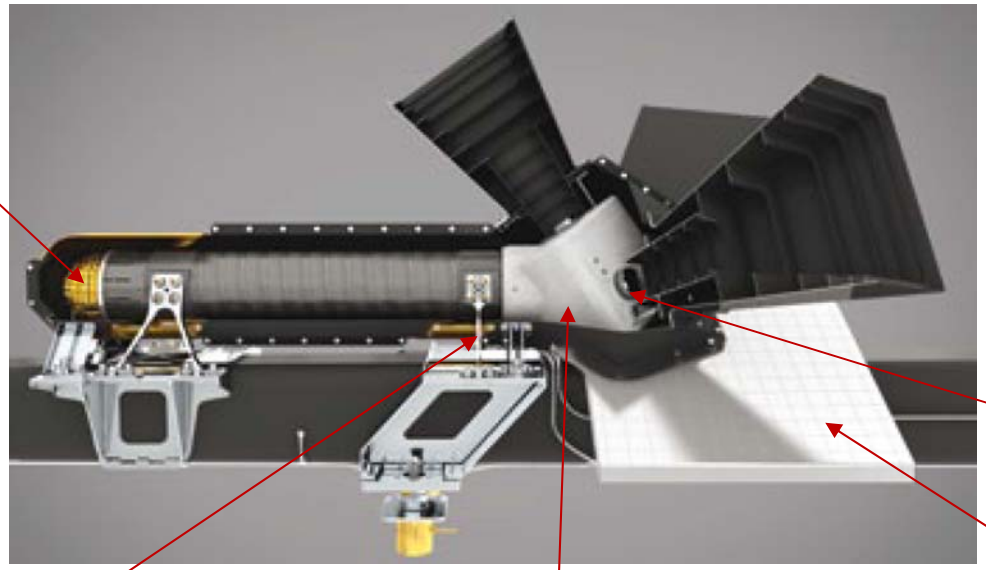


Swarm Optical Bench (OB)

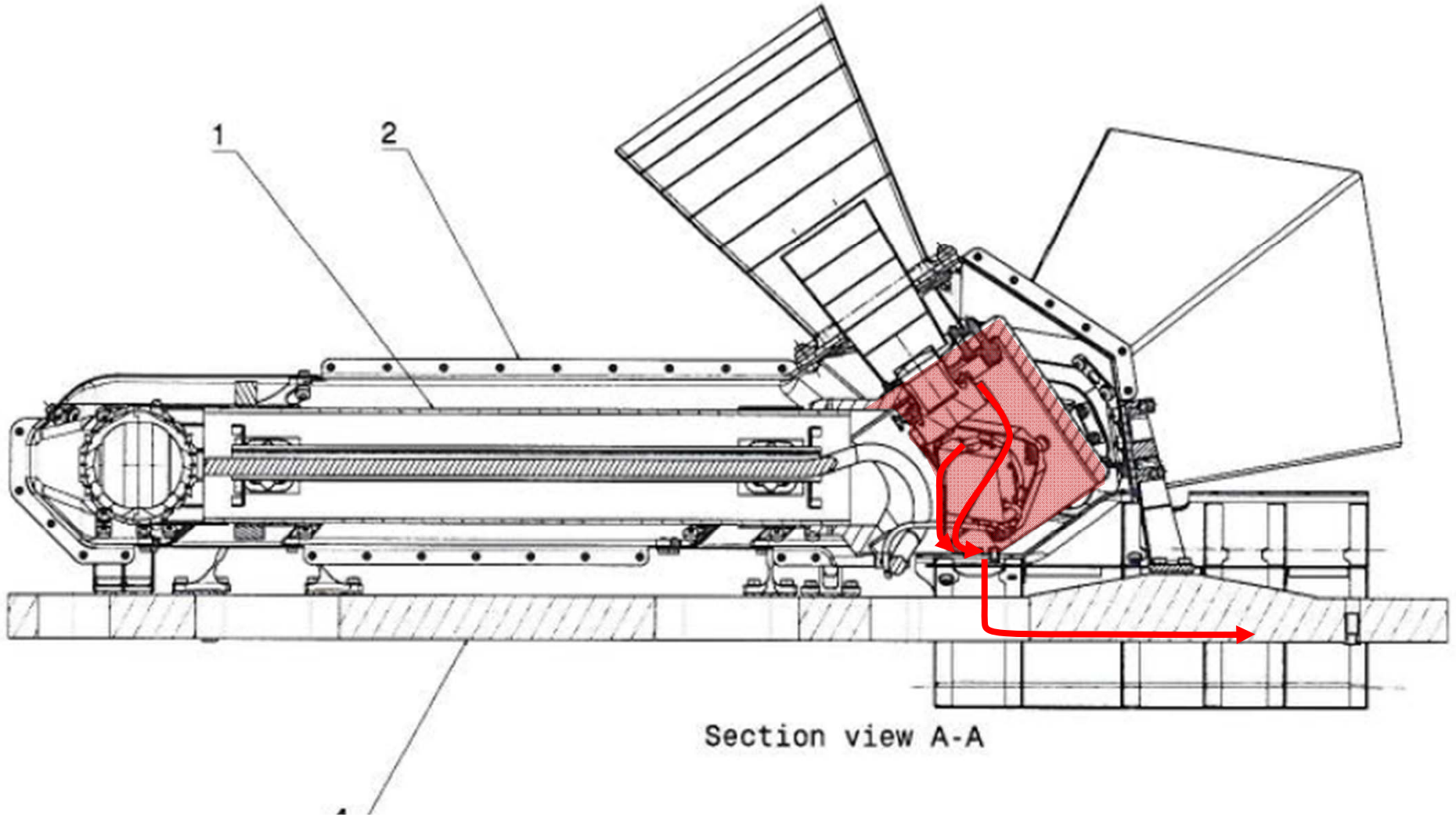


Thermistor name	Thermistor code 1	Thermistor name 2
Hinge	THT00028	TCL_2_ANY_13A_HINGEHNR
	THT00056	TCL_4_ANY_13B_HINGEHNR
	THT00086	TCL_6_ANY_13C_HINGEHNR
Optical bench Boom I/F	**THT00029 (T2)**	TCL_2_ANG_14A_OBBOOMIF
	THT00057	TCL_4_ANG_14B_OBBOOMIF
	THT00087	TCL_6_ANG_14C_OBBOOMIF
Absolute Scalar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

Optical Bench Thermistors



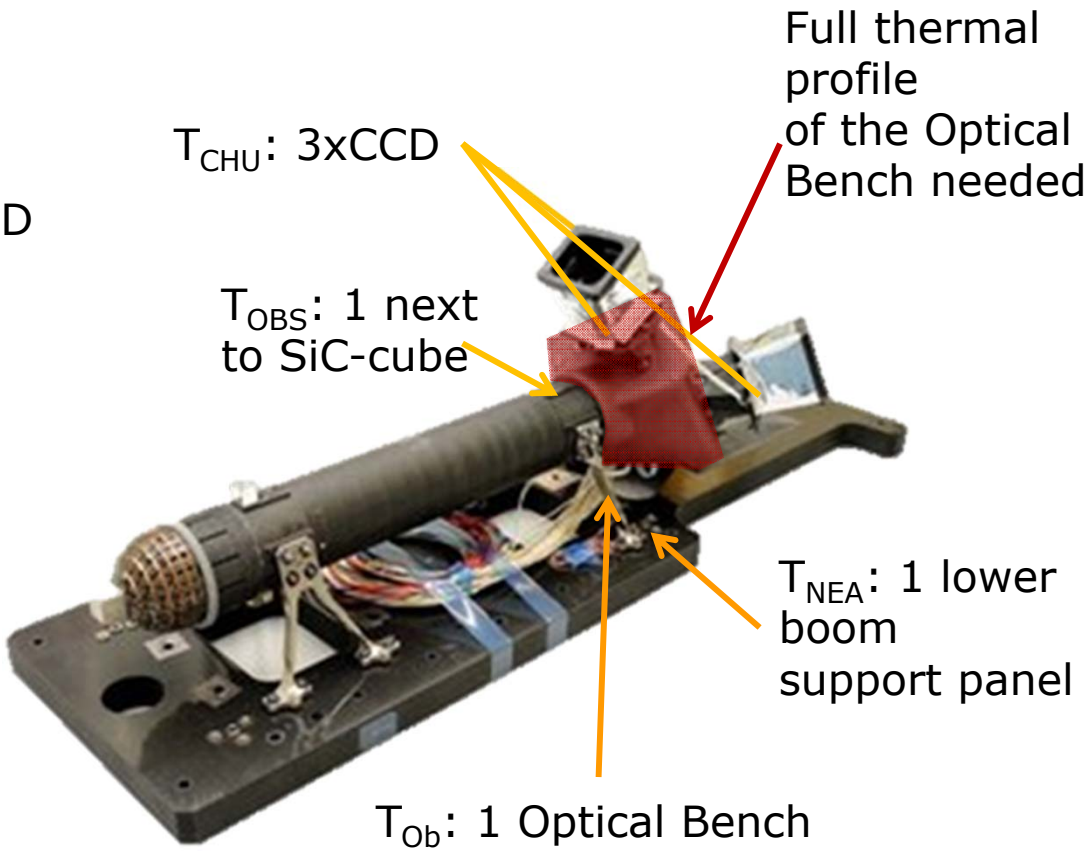
Optical Bench Thermistors



Investigating the temperature profiles

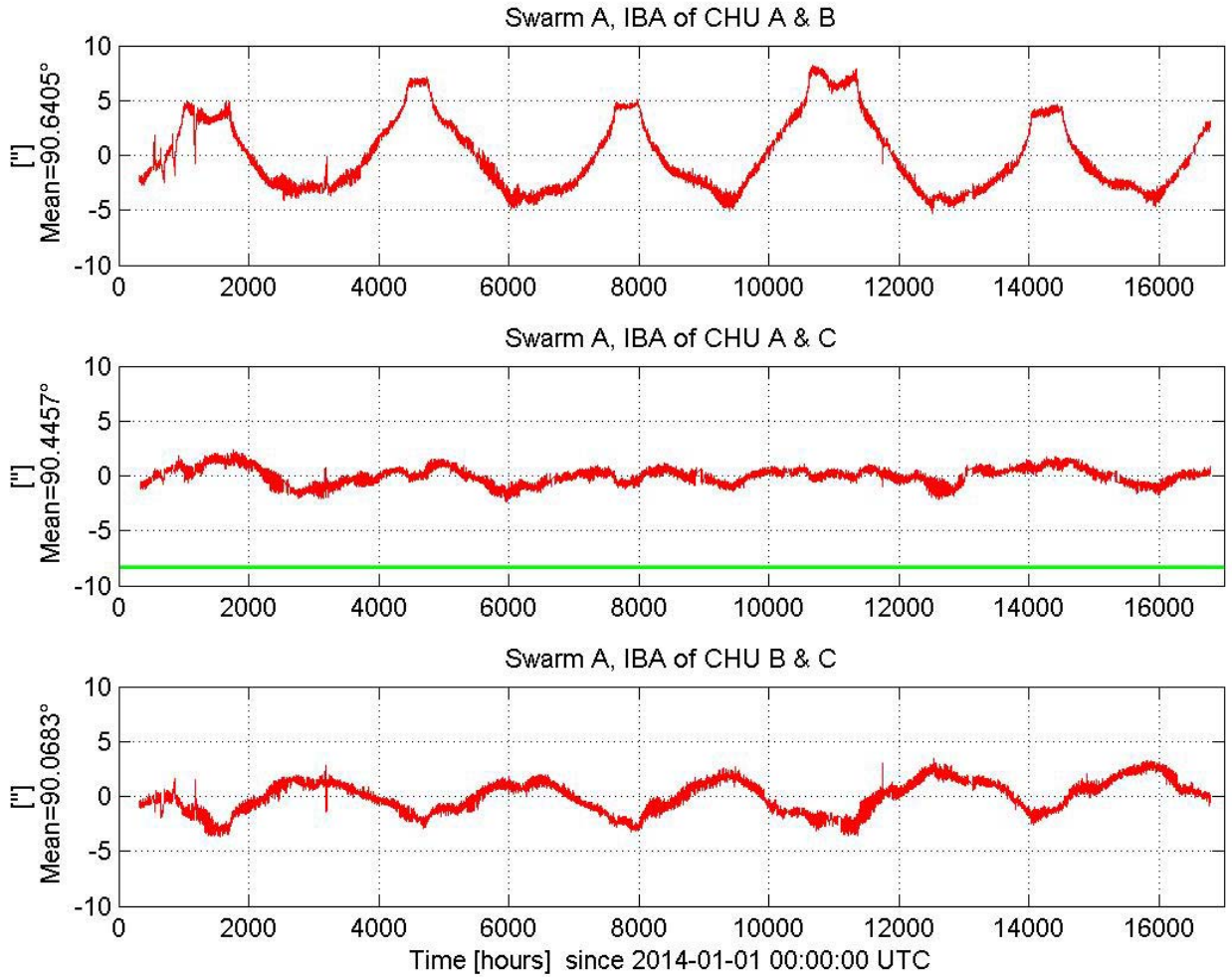
Temperature sensor locations:

- 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

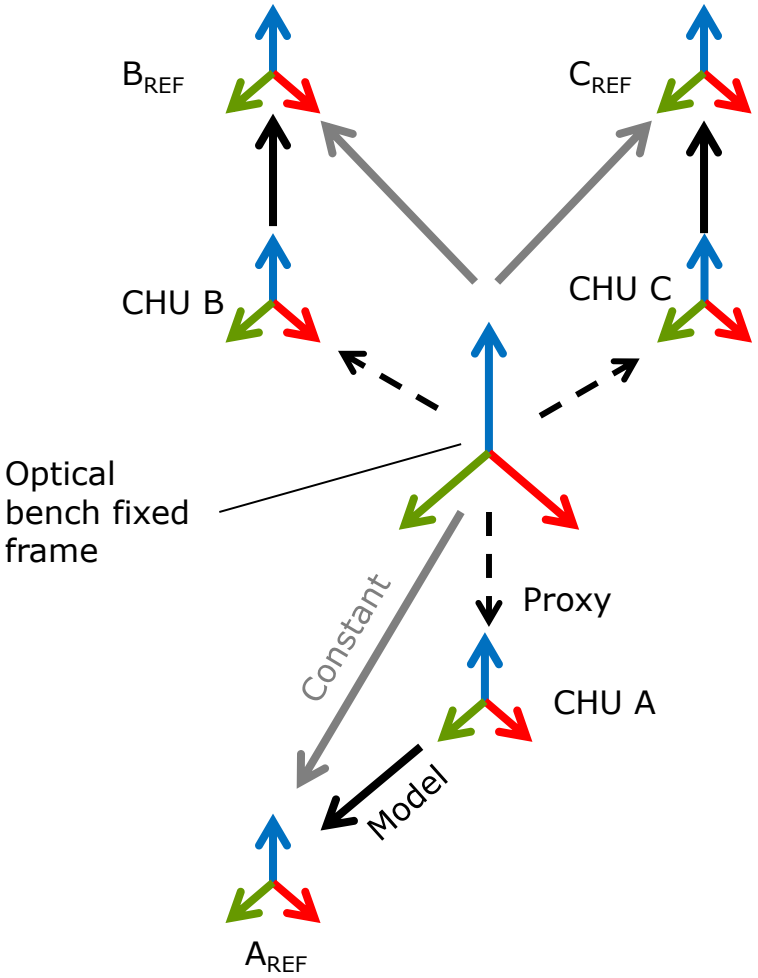


Swarm IBA pairs

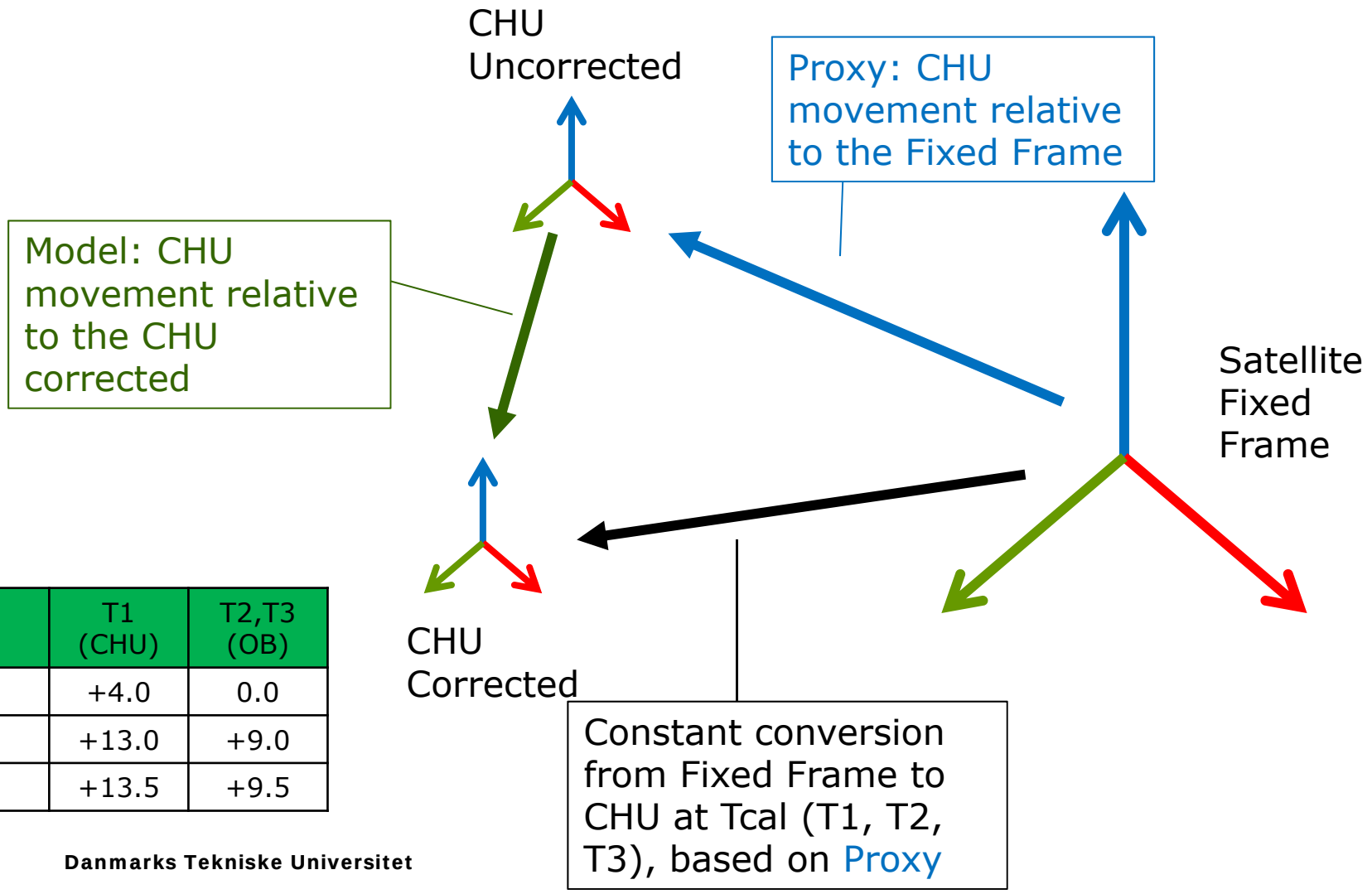
- IBA between CHU A and CHU C does not show clear variation with temperature



Swarm thermal correction model: An overview

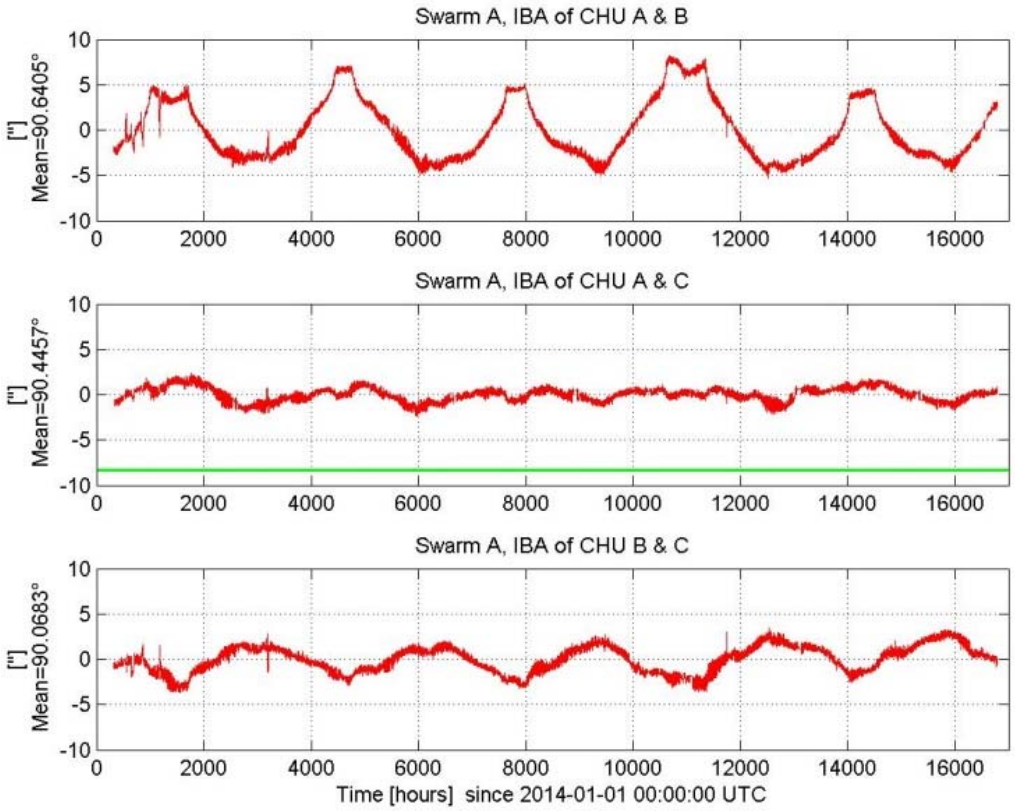


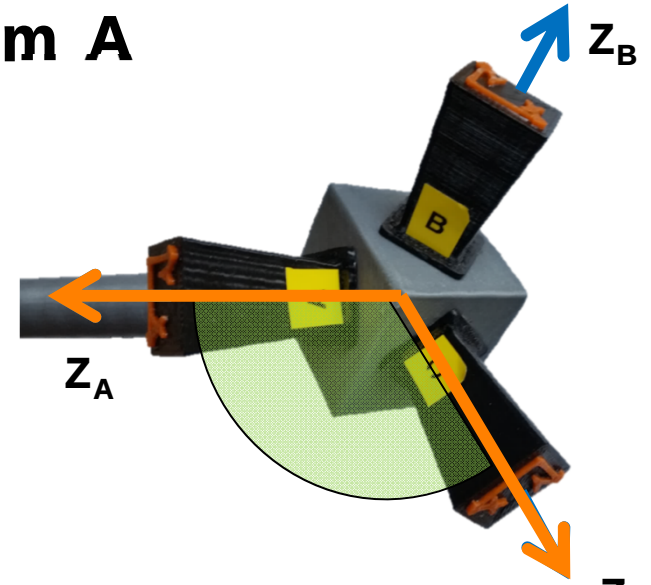
Swarm A Model

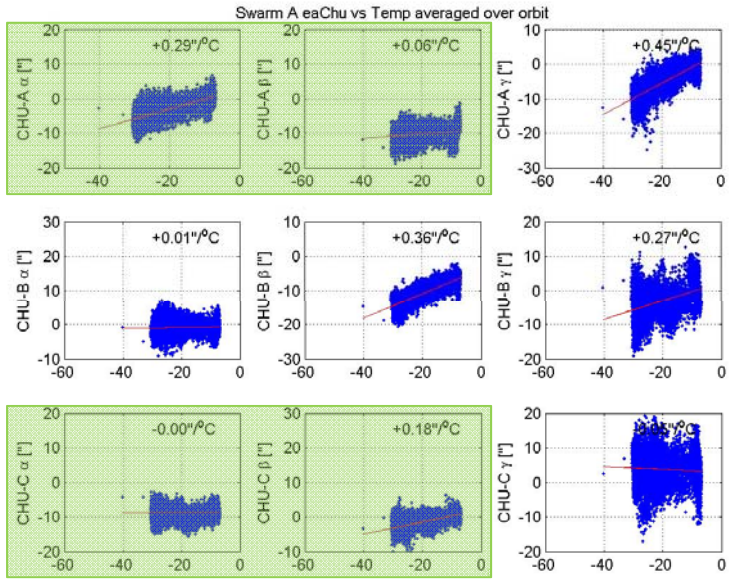


Tcal [°C]	T1 (CHU)	T2,T3 (OB)
Sw-A	+4.0	0.0
Sw-B	+13.0	+9.0
Sw-C	+13.5	+9.5

Fixed frame construction Swarm A





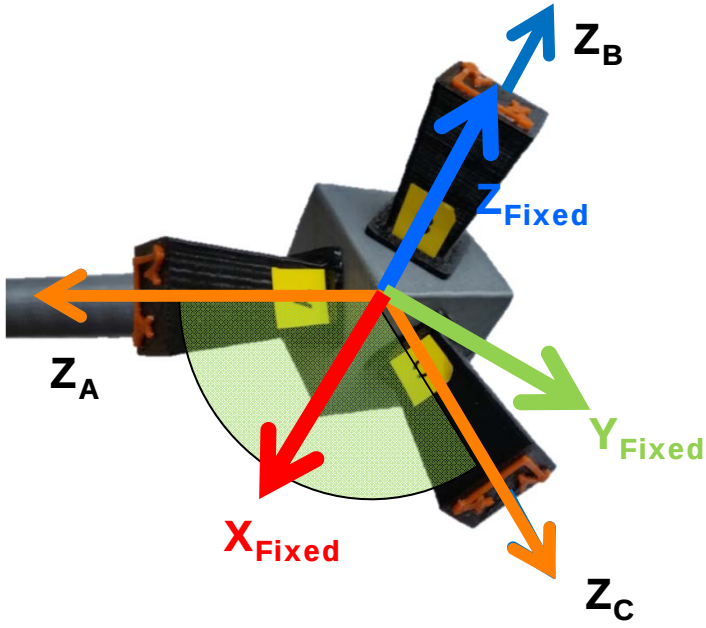


Swarm correction application: Fixed frame construction

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

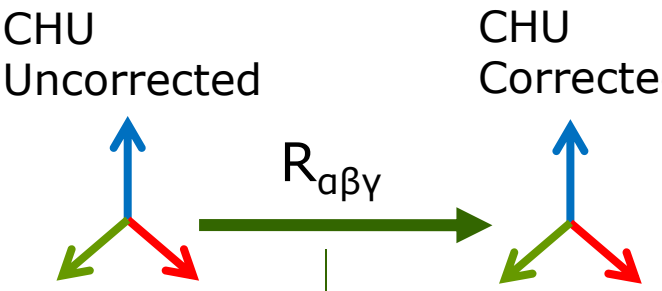
$$X_F = \frac{Z_A + Z_C}{|Z_A + Z_C|}$$

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



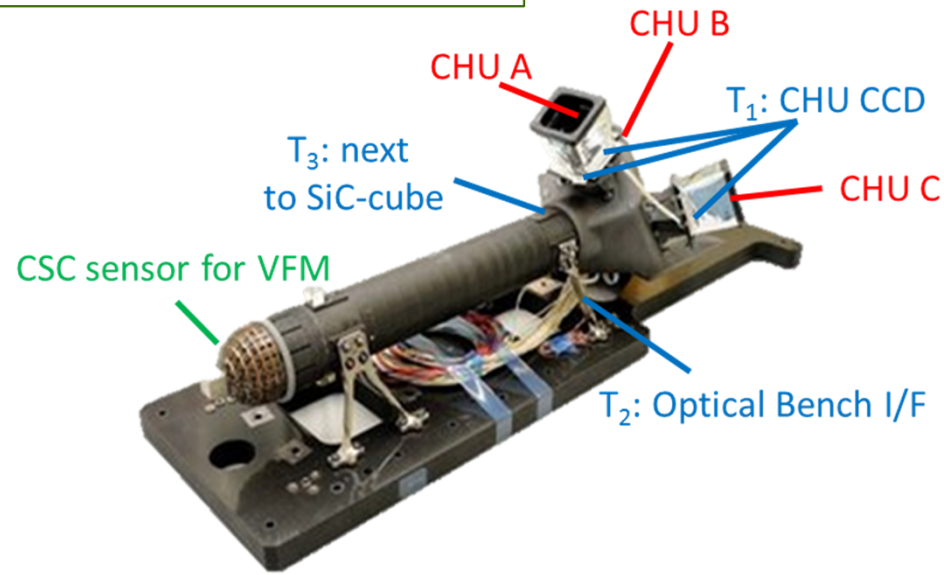
- Small residual free rotation:
  - Fixed relative to the VFM
  - Different in the three Swarm satellites
  - If it spills, it would go to the VFM and it will be fixed rotation over the full mission span

Swarm thermal correction model formulation



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

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



- Thermal model is not perfect since it is constructed using the best temperature flow gradients proxy

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]

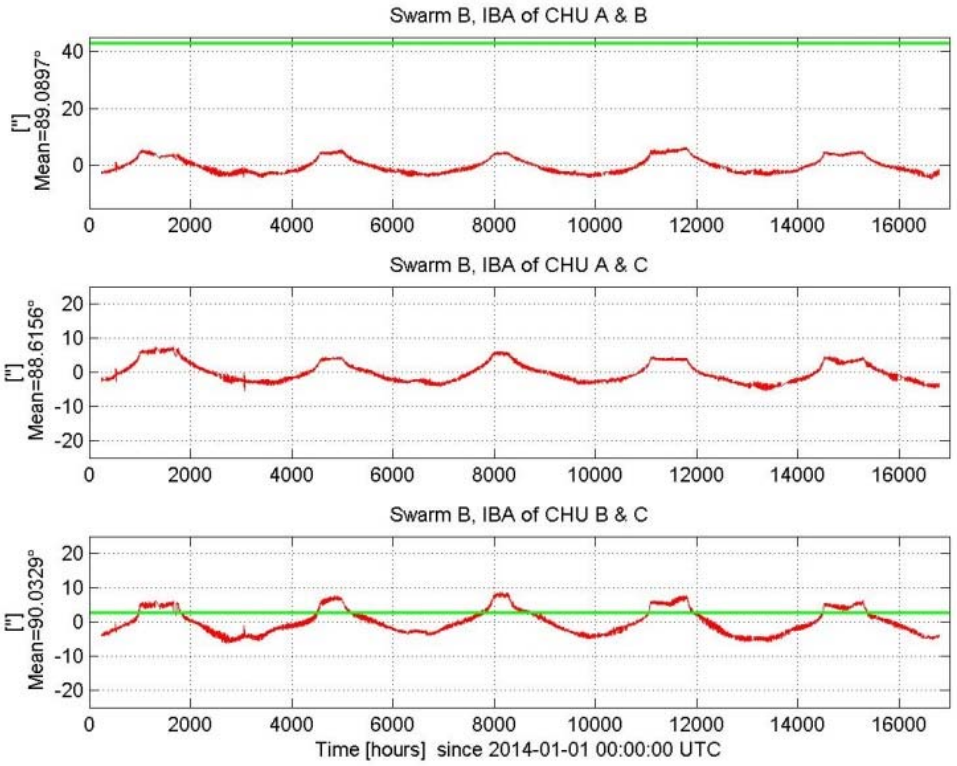
CHU B

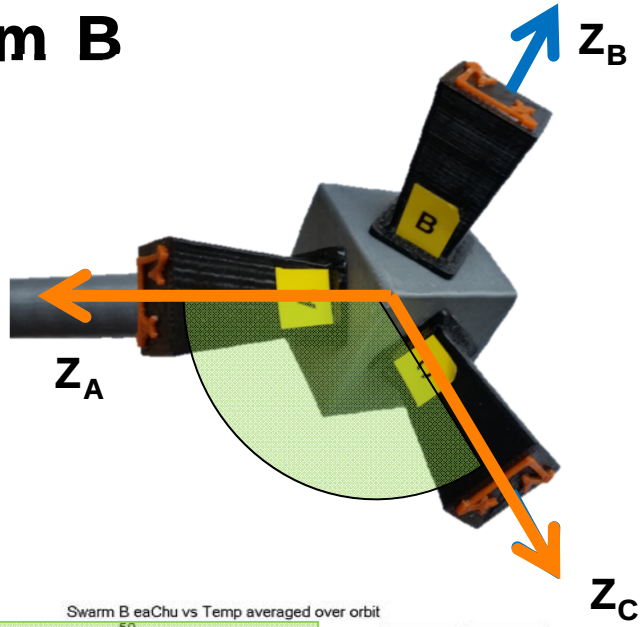
		alpha	beta	gama	
	Constant	-1.19000e+00	2.03750e+00	5.51564e+00	["]
	T_CHU_B	3.27044e-01	-4.03134e-01	-3.12725e-02	["/°C]
T029	- T_CHU_B	-2.10603e-01	4.04762e-02	-7.31304e-01	["/°C]
T032	- T_CHU_B	2.40148e-01	6.57657e-02	2.07894e+00	["/°C]

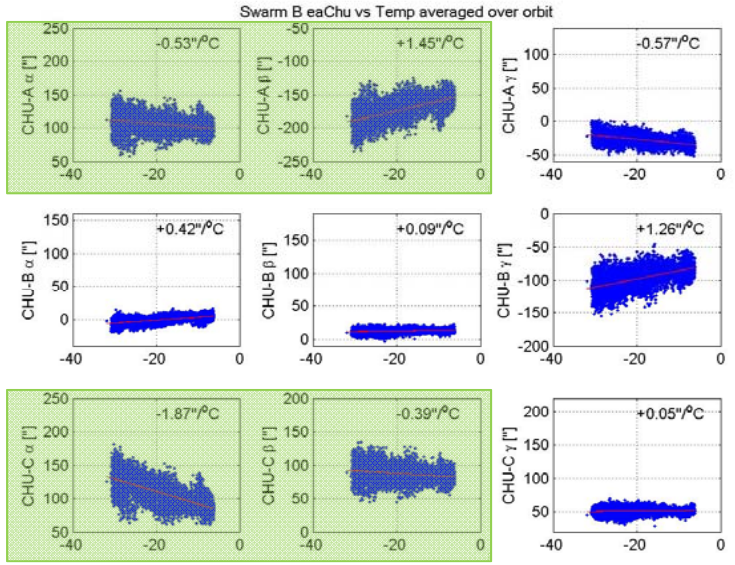
CHU C

		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 correction application: Fixed frame construction Swarm B







Swarm B model

Modelling period:

12-May-2014 01:00:05 (2014-131)
~3000h

to

03-Dec-2015 22:18:07 (2015-337)
~17000h

Swarm B Fixed Frame Type=16

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]

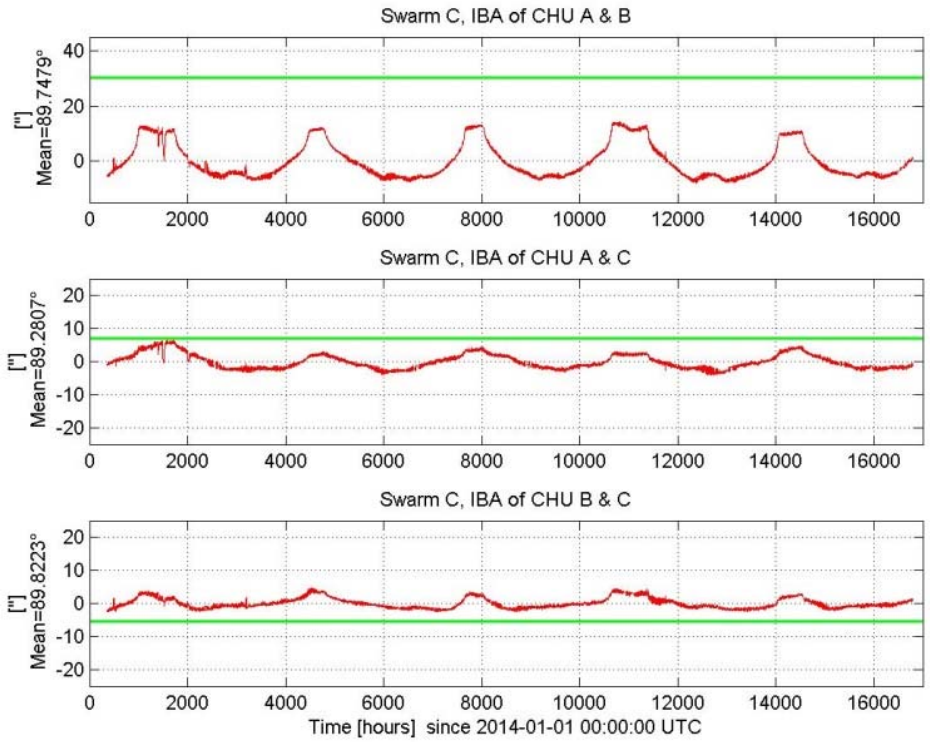
CHU B

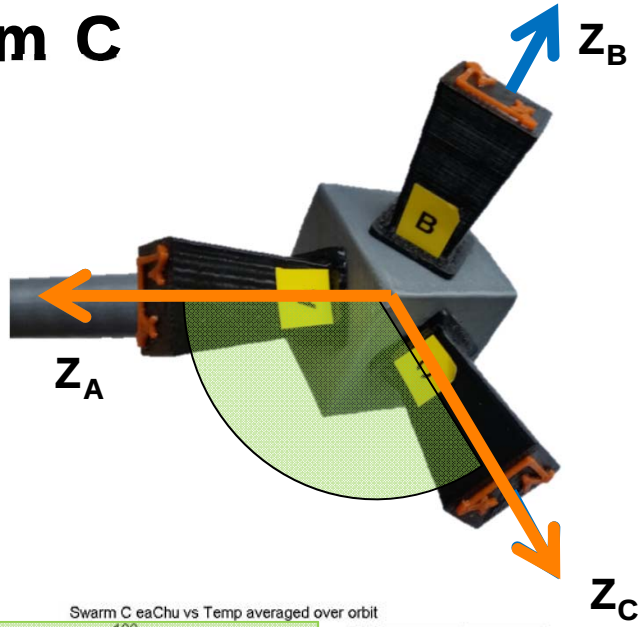
		alpha	beta	gama	
	Constant	-5.15861e+00	-1.26225e+00	-2.48957e+00	["]
	T_CHU_B	5.28498e-01	1.34662e-01	3.97005e-01	["/°C]
T029	- T_CHU_B	-5.56507e-02	1.06394e-01	-4.76603e-01	["/°C]
T032	- T_CHU_B	4.83616e-01	1.56951e-02	1.14448e+00	["/°C]

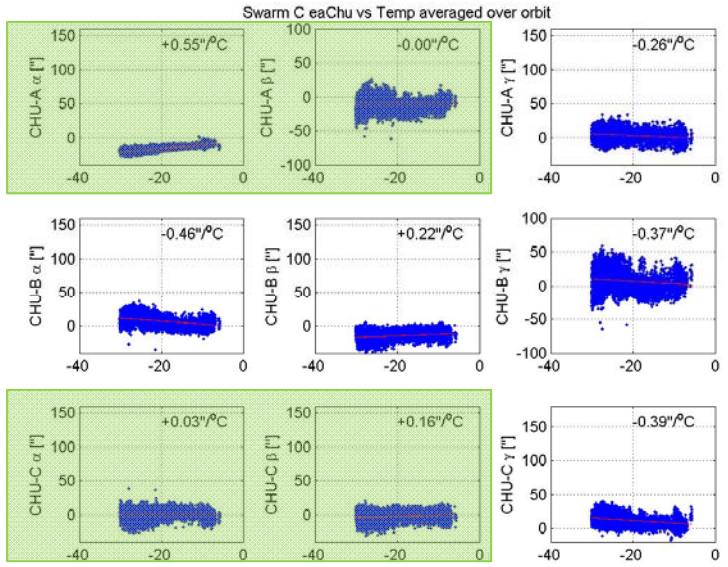
CHU C

		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 correction application: Fixed frame construction Swarm 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]

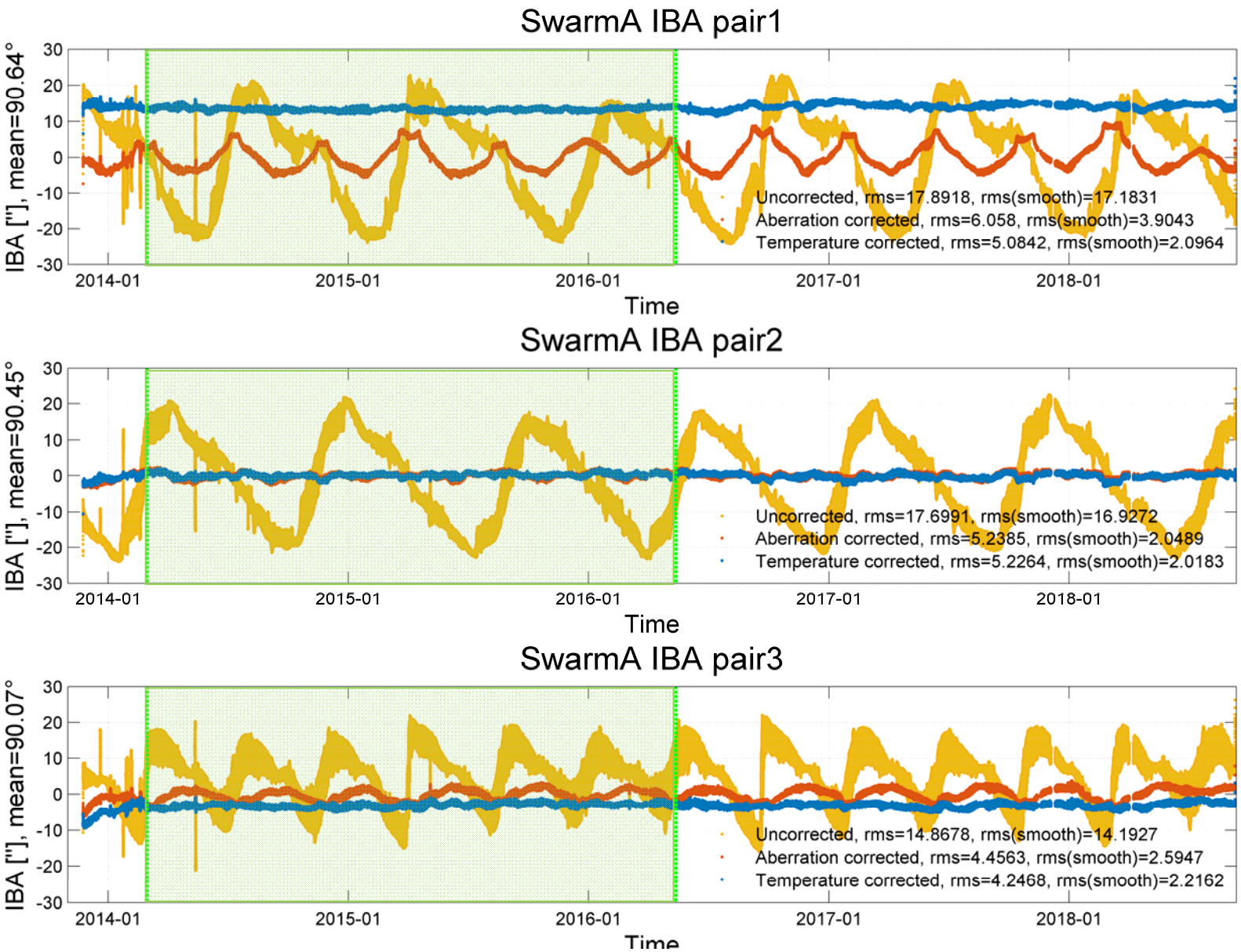
CHU B

		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]

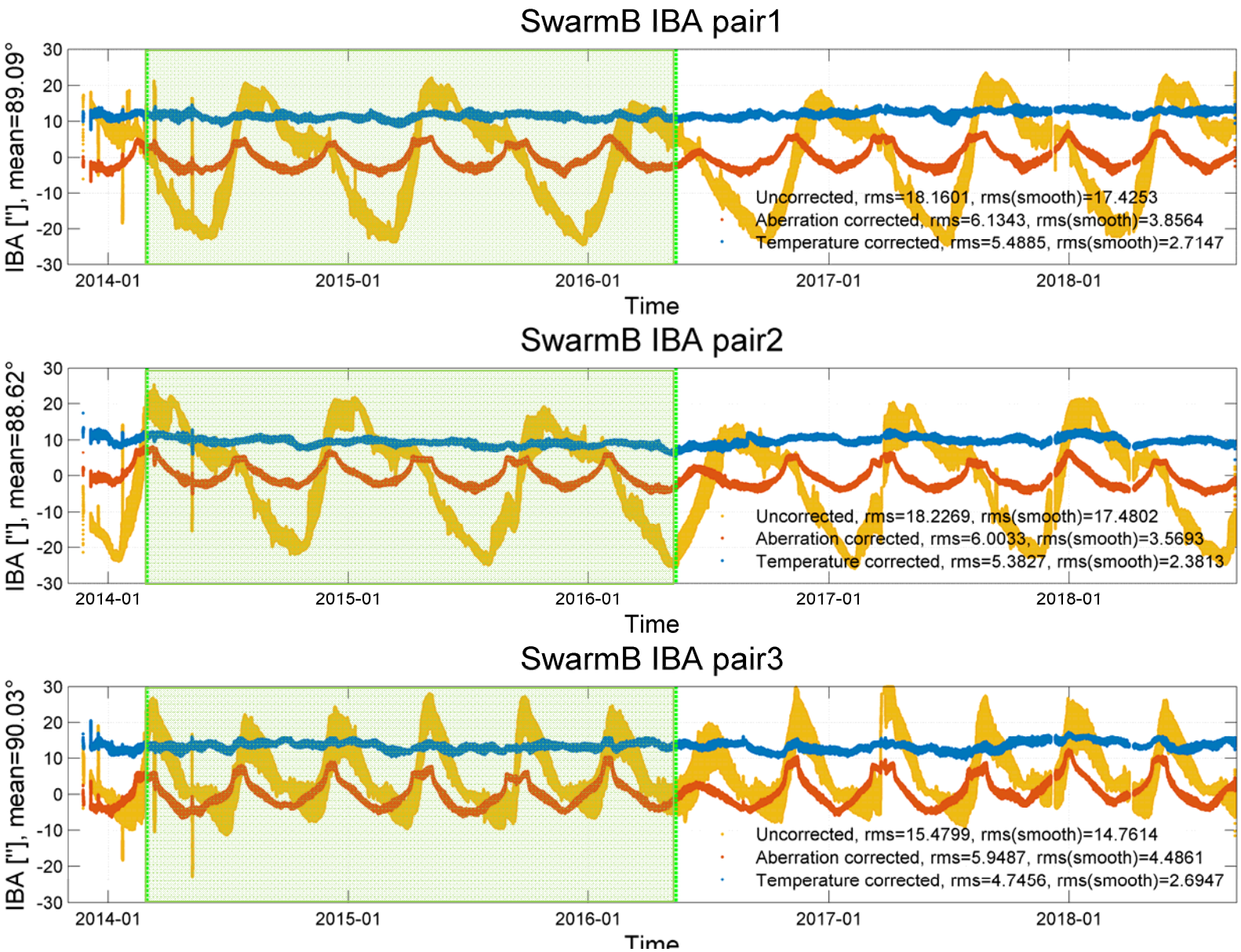
CHU C

		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]

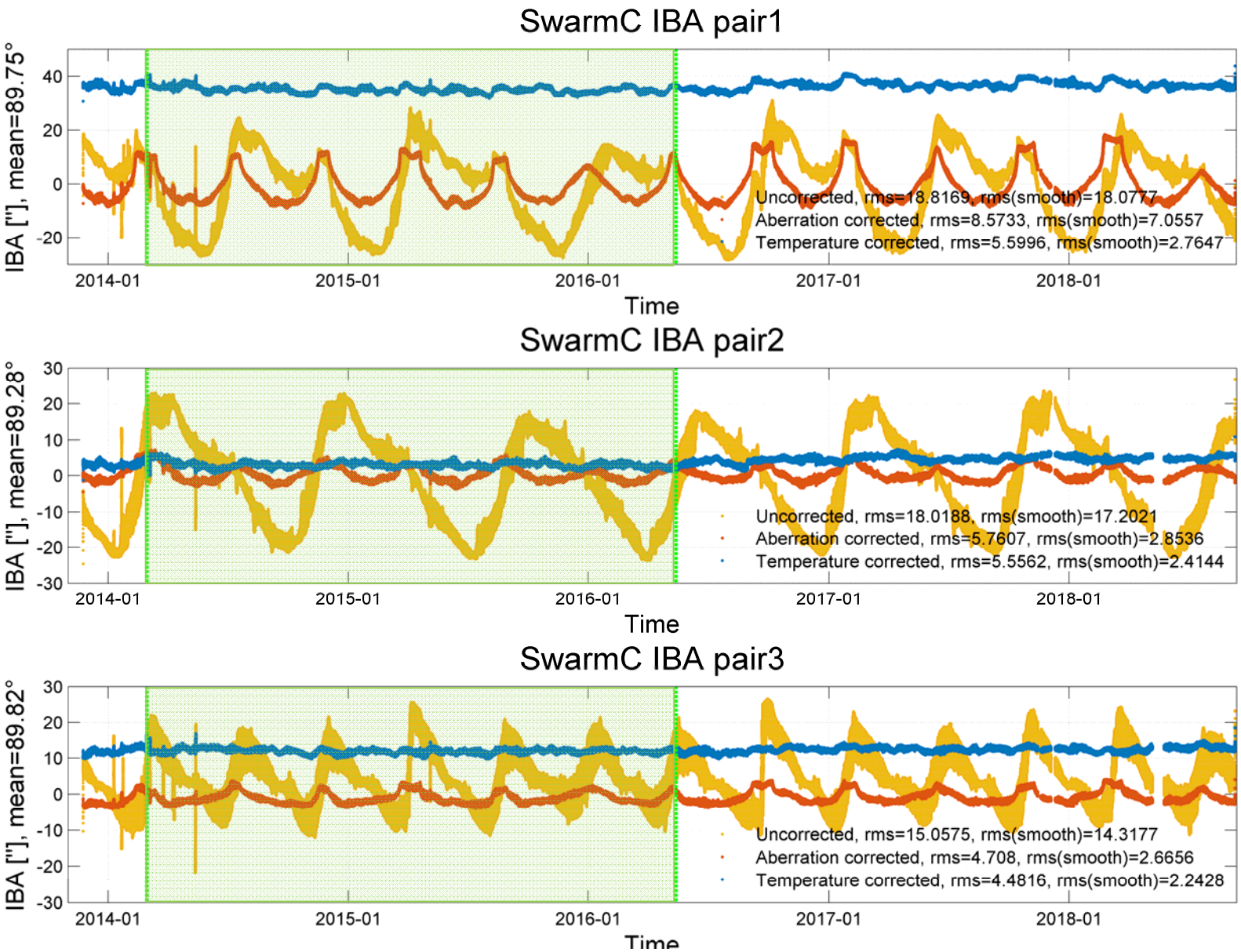
Correction effects Swarm A IBAs



Correction effects Swarm B IBAs



Correction effects Swarm C IBAs

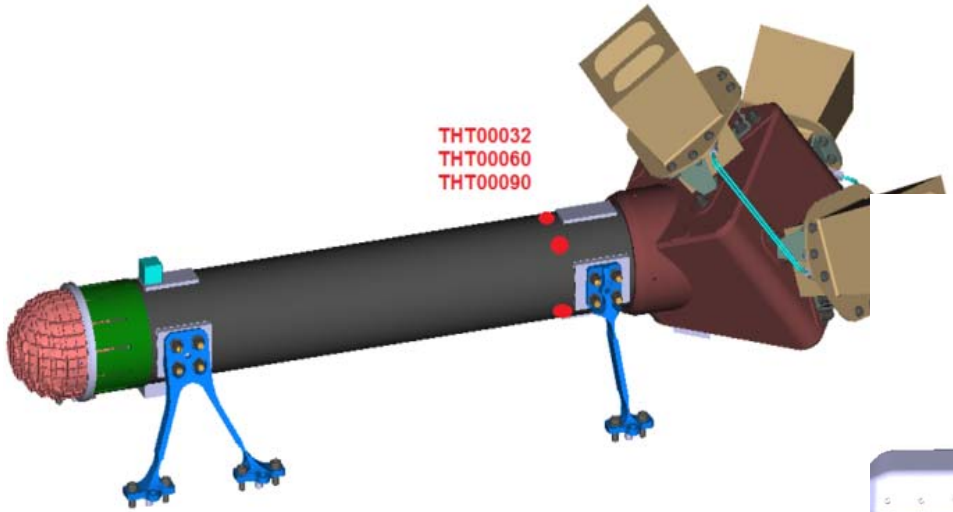


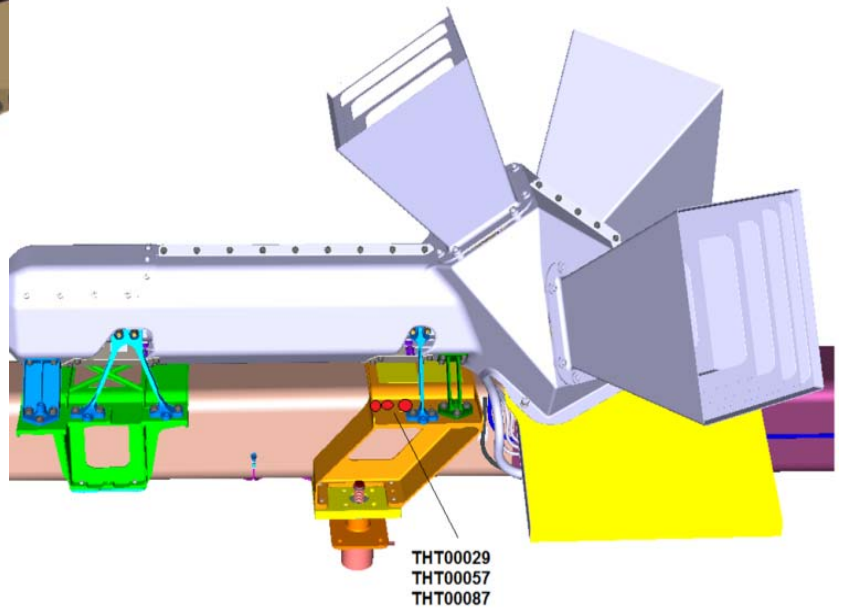
Conclusion

- µASC and its baffle system performs as designed
- IBA variation correlates with temperature gradients measured on the OB
  - Correction model for the thermo-elastic instability is constructed
- Long term application **outside model interval show excellent agreement**
- Analysis shows that IBA variation is not caused by the instrument, but is **fully thermally driven**
- The root cause – thermal variation between the OB and the radiator through thermal straps.
  - Majority (~80%) of the thermal variation is in the direction of the heat dump cable (from CHU and radiators)
  - ~20% from the other thermal gradients across the cube

Backup slides

Temperature

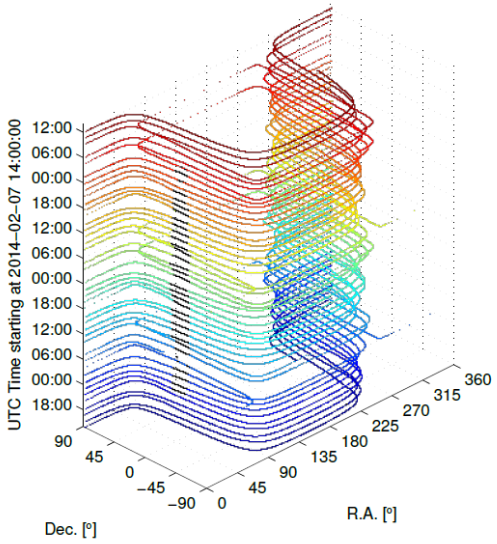




Star Tracker (STR):
Availability

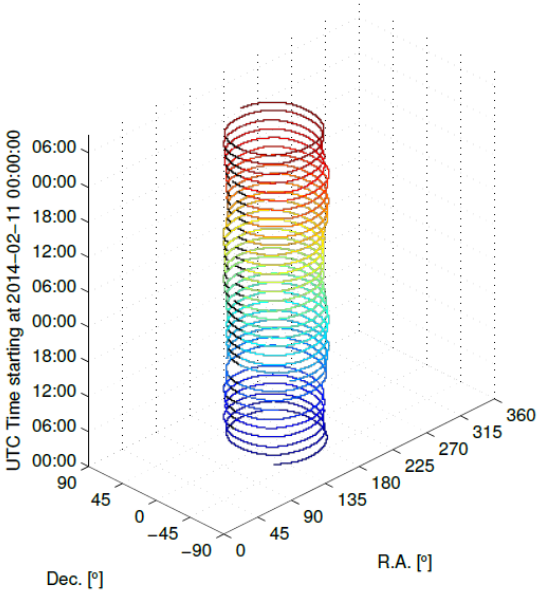
A Star Tracker must deliver valid updates when viewing nominal star fields, and exhibit graceful degradation when entering star fields with e.g. bright objects.

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.

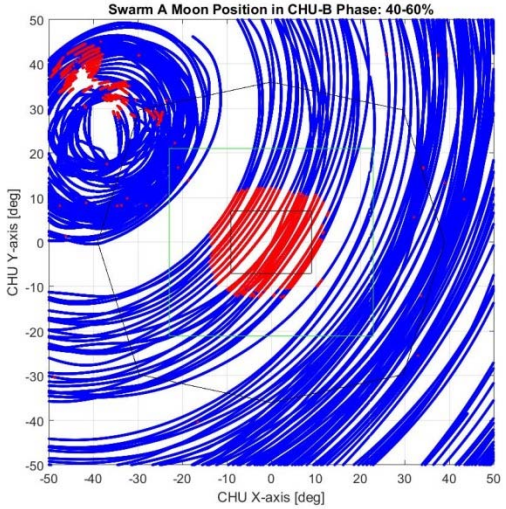
Star Tracker (STR):
Availability of 2 or 3 sensor solutions

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.

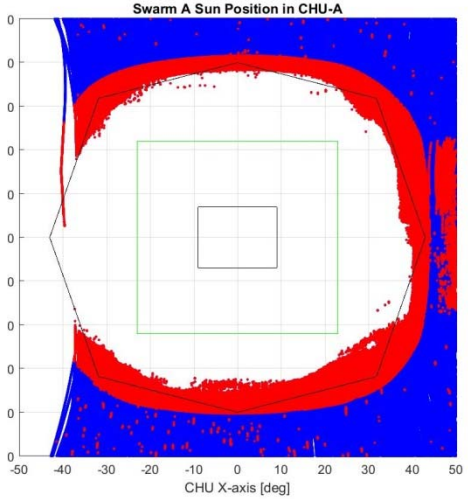
- Inflight performance of the sensor baffle systems are better than designed

- Inflight performance towards a 50% Moon show full resilience

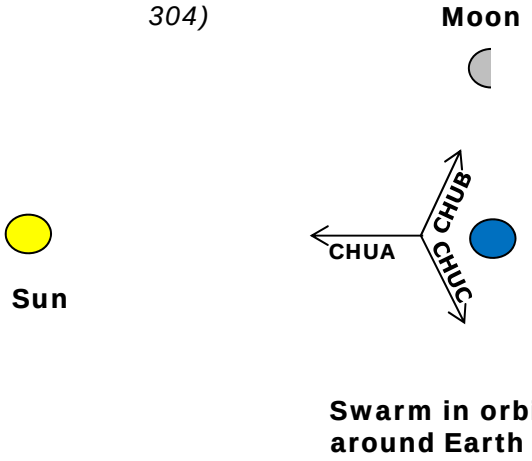
Demonstrating that 2 or 3 sensor solutions are granted, with excellent margins, for the planned mission profile.

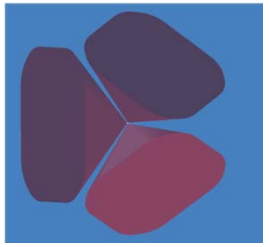


Operations vs Moon:
Position of 40-60% Moon in Swarm A CHU-B, Valid attitudes, with BBO flag(red), 184 days data (2015-121 -> 304)



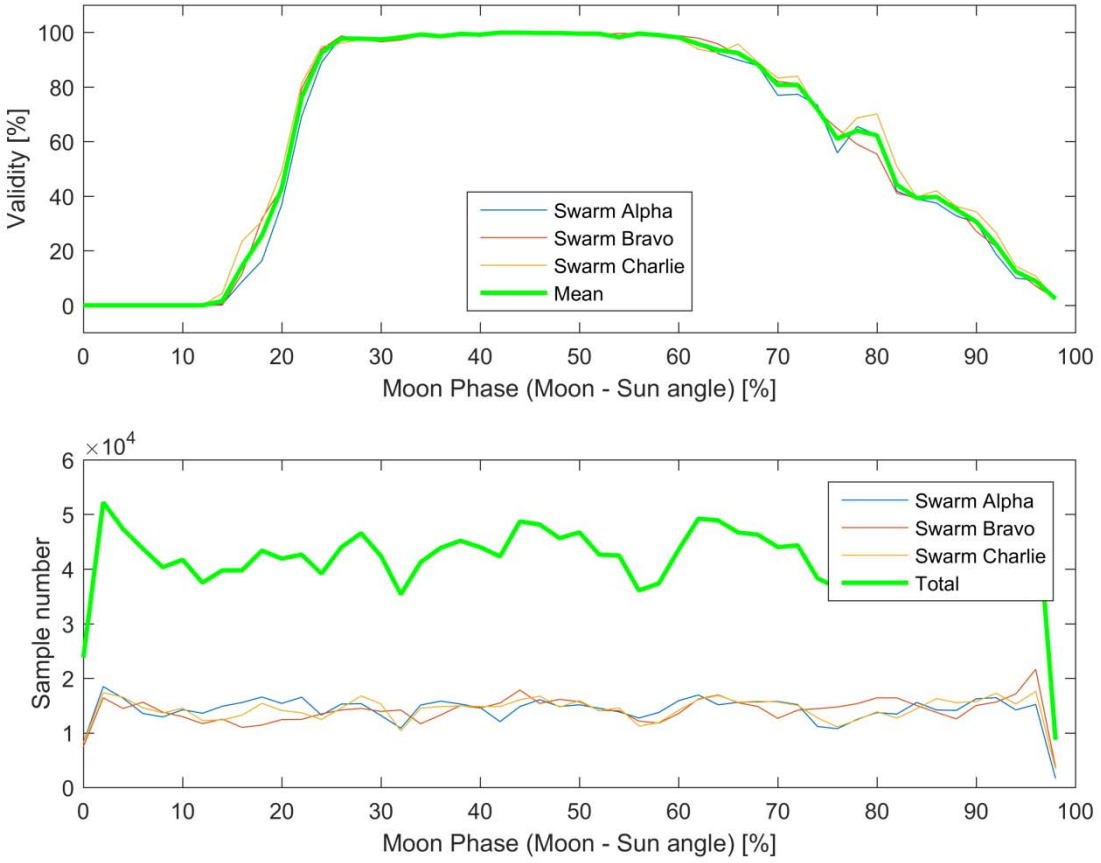
Baffle performance vs Sun:
Position of Sun in Swarm A CHU-A, Valid attitudes, with BBO flag(red), 184 days data (2015-121 -> 304)





Baffle performance: Swarm Sun Exclusion cones

Effect of the moon phase on the SWARM ASC observation validity

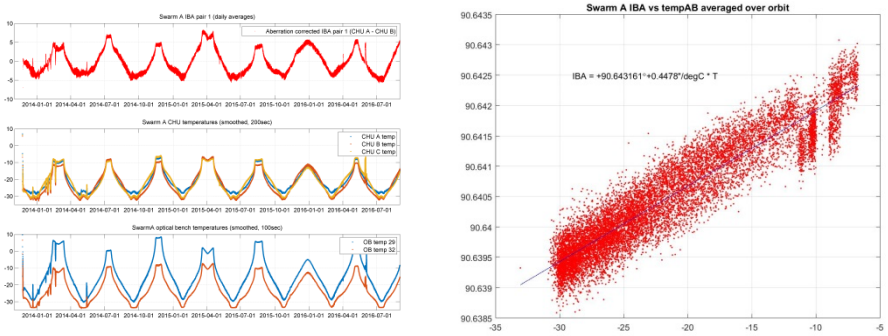


Star Tracker (STR):
Accuracy

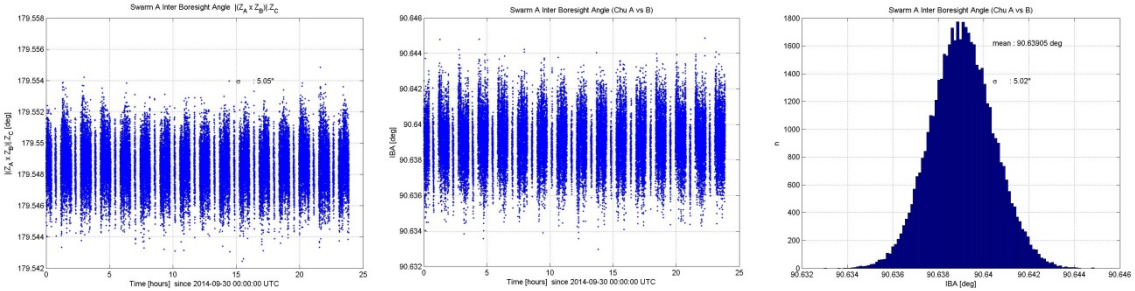
Accuracy of the Swarm STR system is best evaluated by comparing the attitude measurement of one sensor to the combined attitude from the other two.

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.

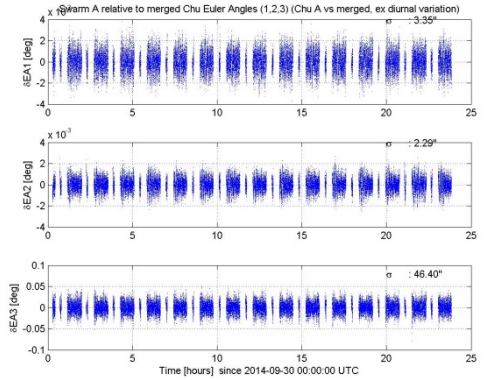


Stability of optical cube: Deep anomaly investigation…



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

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



1,2,3 Euler rotation

3.25”

2.29”

46.40”

Star Tracker (STR):
BBO flag

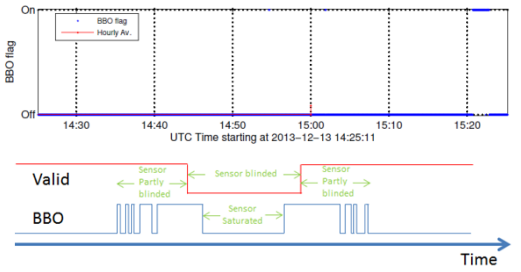
A Star Tracker attitude measurement may be disturbed, if a bright object enters the FoV.

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.

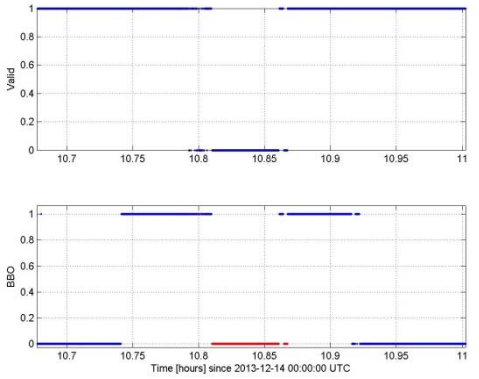
Since launch, the STR systems on all three Swarm satellites have experienced unexpected triggering of the BBO flags at certain times.

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

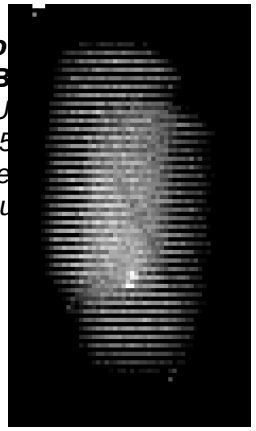
Sporadic triggering of BBO: *Swarm A, CHU A, 2013 13 Dec. 14:55:10 UT, BBO time line and acquired image*



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



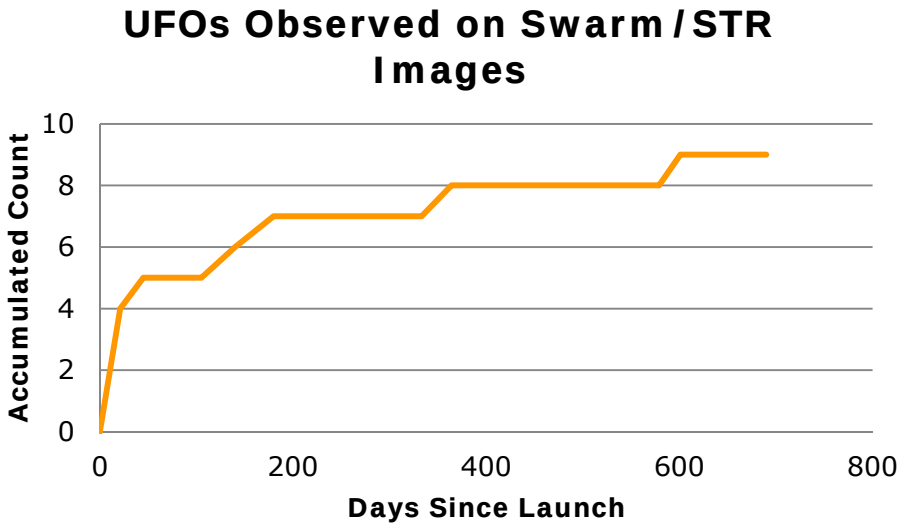
Spo
of B
CHU
14:5
time
acqu



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		
2015 - Aug	0		
2015 - Sep	0		
2015 - Oct	0		



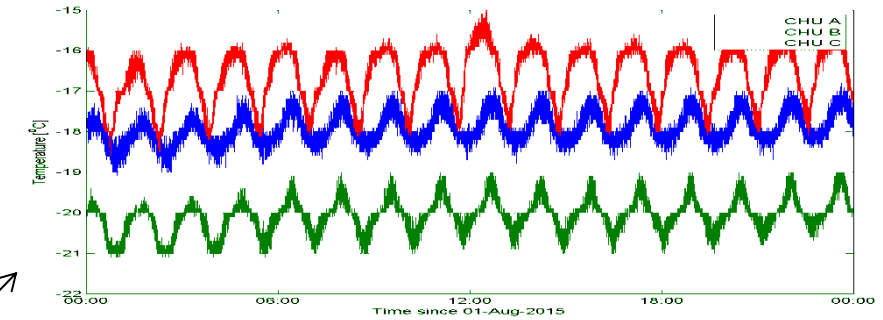
Star Tracker (STR):
Thermal stability

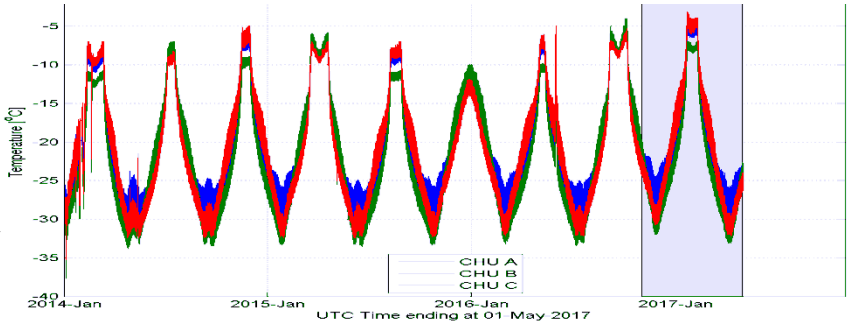
Data 2014/01/01 to 2016/10/31

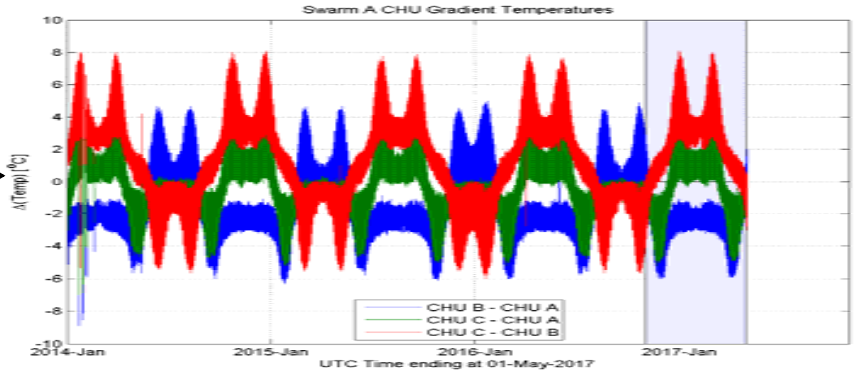
Star Trackers thermal stability is a significant parameter for performance, and thorough thermal design in form of Optical bench, heat pipes, radiator and baffle finished has been implemented.

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

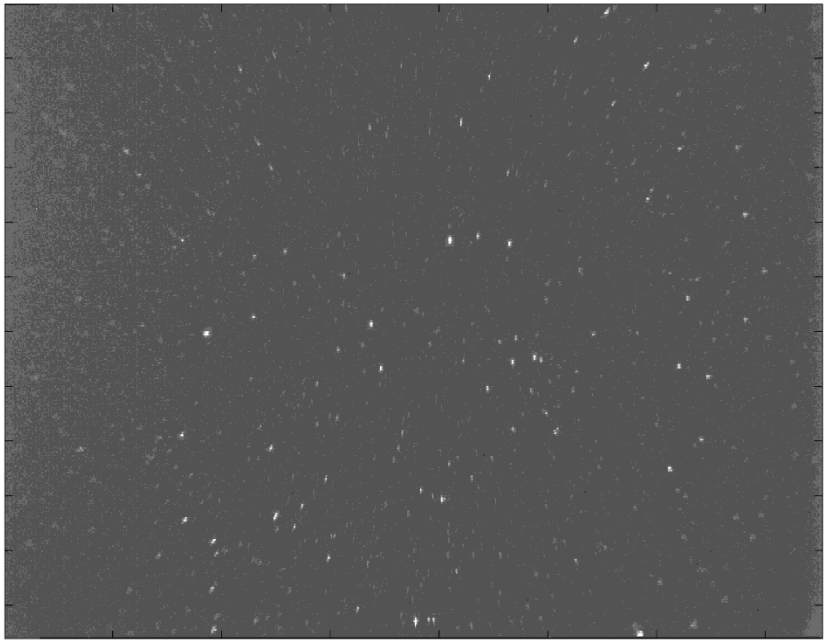






Star Tracker (STR): Instrument Aging

- 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	CHU-A (SW-C001-C2)	514041010	<10	Healthy
	CHU-B (SW-C001-C3)	514050010	<5	Healthy
	CHU-C (SW-C001-C4)	514044010	<5	Healthy
SwB	CHU-A (SW-C001-C8)	514038010	<10	Healthy
	CHU-B (SW-C001-C9)	514043410	<5	Healthy
	CHU-C (SW-C001-C10)	514050010	<5	Healthy
SwC	CHU-A (SW-C001-C5)	514041010	<10	Healthy
	CHU-B (SW-C001-C6)	514050010	<5	Healthy
	CHU-C (SW-C001-C7)	514047010	<5	Healthy

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

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

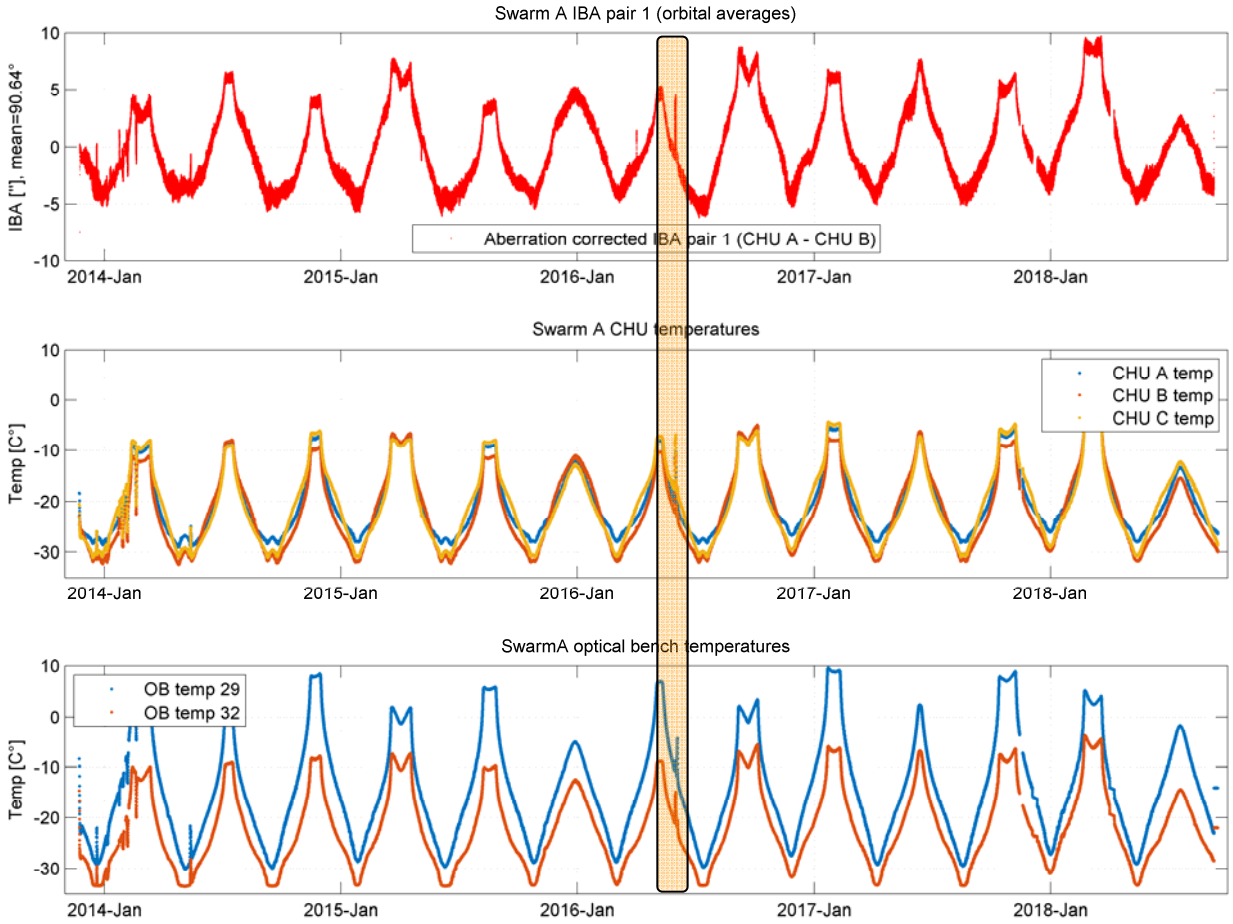
- Remove outliers in House Keeping Temperatures (T<-35)
- Smooth temperatures with moving average filter of 400 sec width
- Interpolate temperature on attitude times
  (Extrapolation: Assign last value for points outside the domain)

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

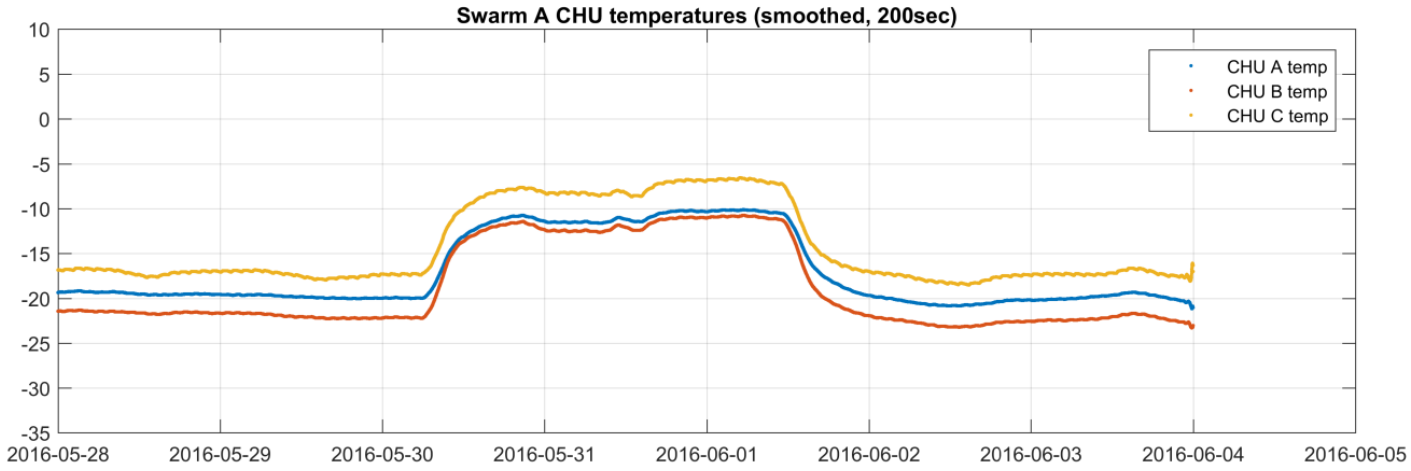
- Two heaters located around the optical bench (OB)
  - an operational heater (id 21) mounted on the radiator plate of the OB,
  - a powerful survival heater (id 01) located on the OB interface bracket.

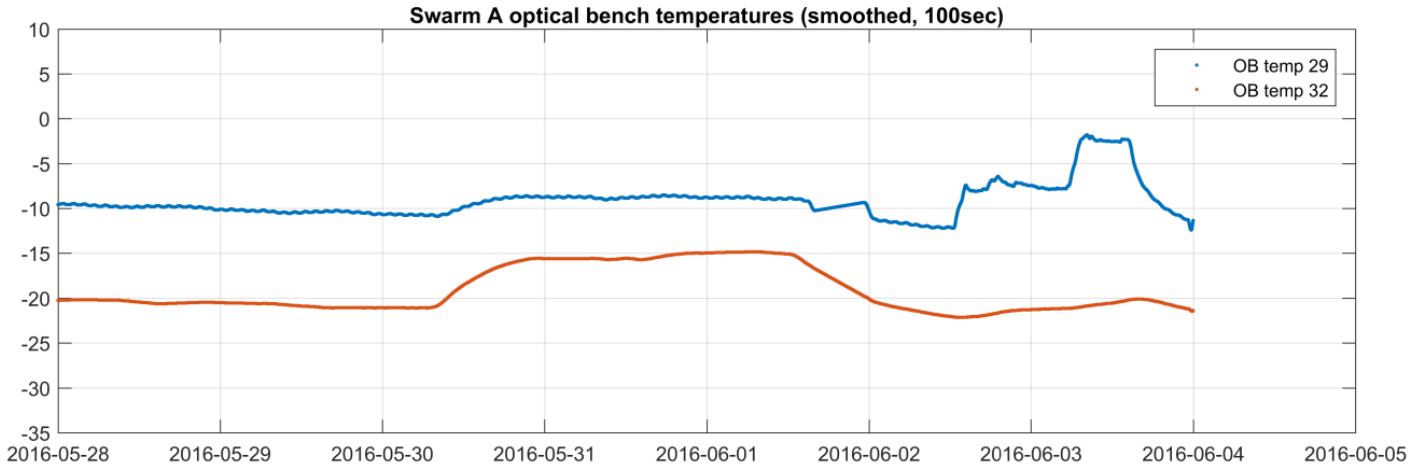
Time	Heater	Set-point [°C]	Comment
2016-05-30 07:21:28	21	-15	Heater predominantly on.
2016-05-31 13:03:20	21	-10	Heater not powerful enough to reach the set-point, i.e. heater constantly on
2016-06-01 12:24:48	21	-33	Nominal setting
2016-06-02 13:17:52	01	-9/-7	Set-point temperature quickly reached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

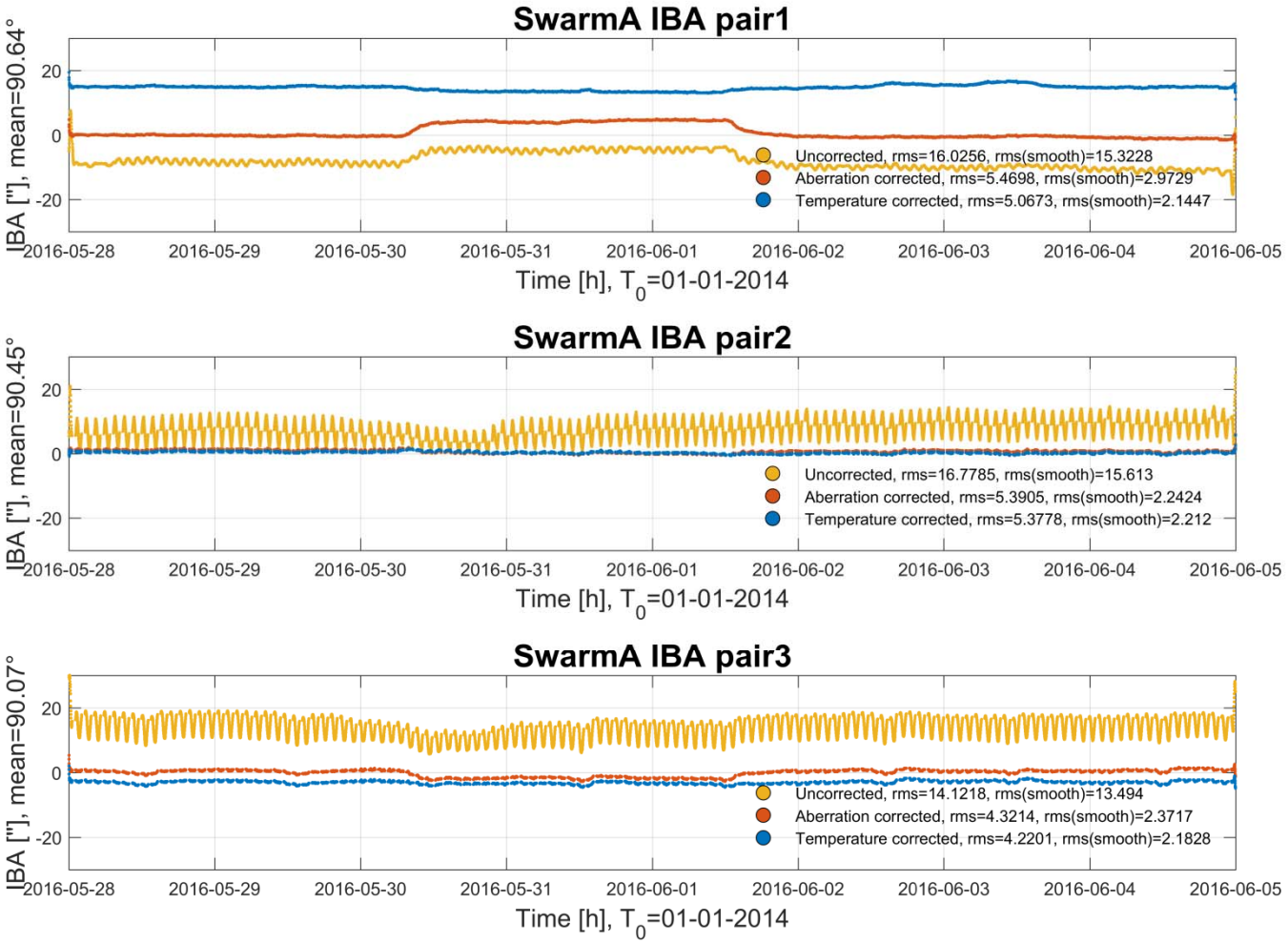


Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)

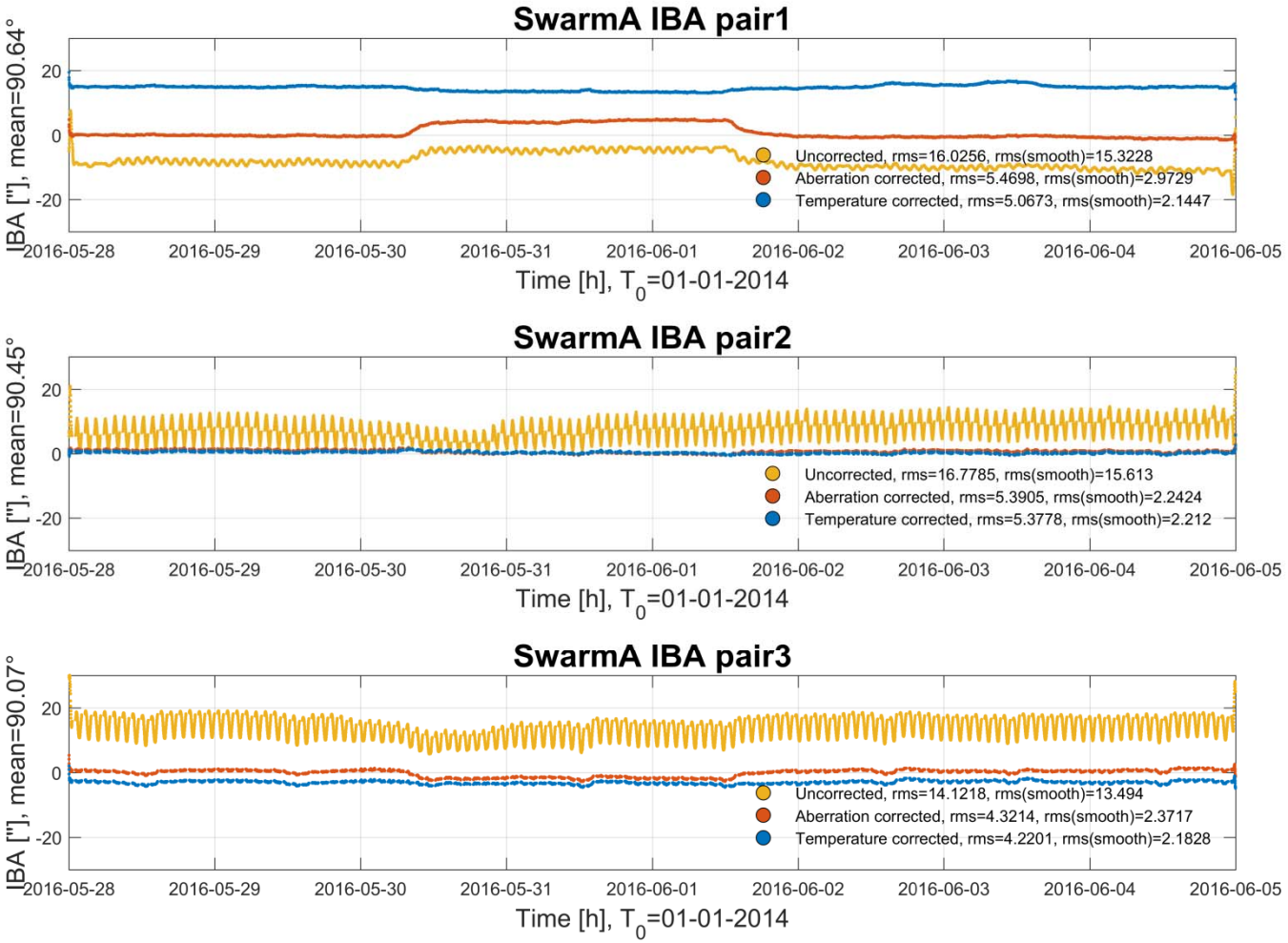




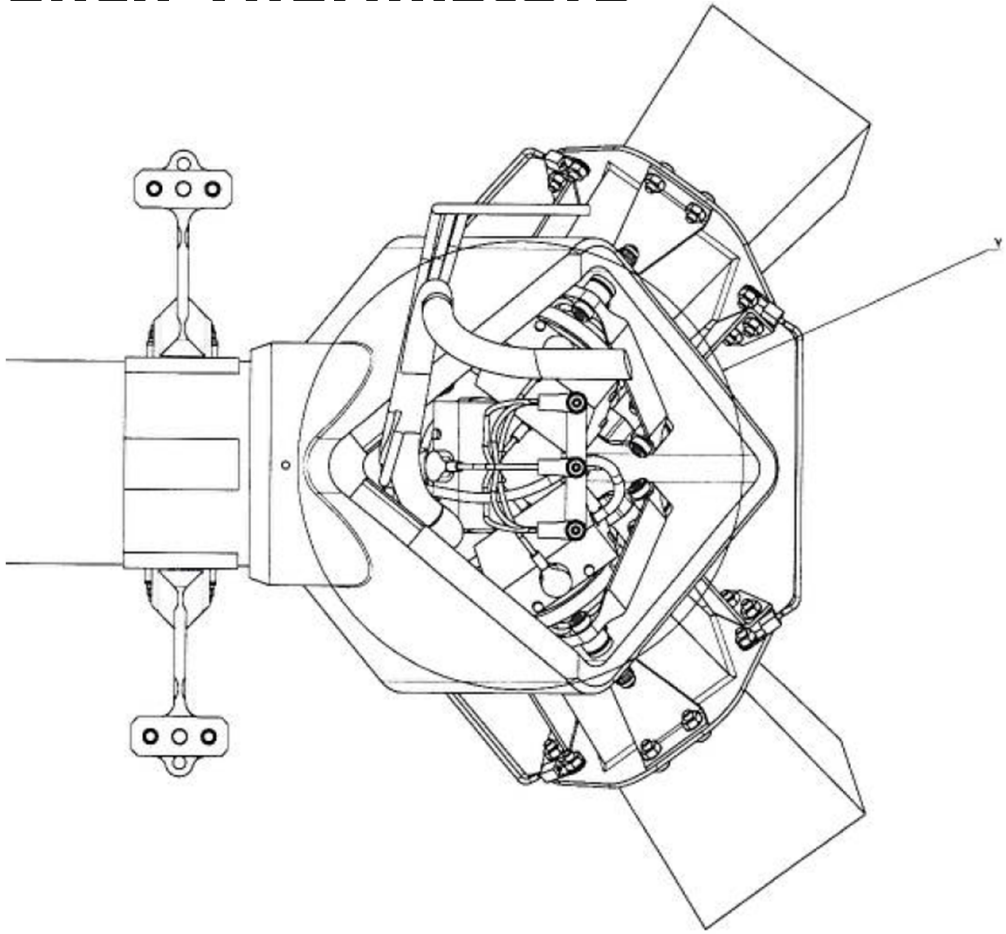
Optical Bench Heater Test on Swarm Alpha for ASM-VFM residual investigation (29.05.2016 - 02.06.2016)



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



Optical Bench Thermistors



Optical Bench Thermistors