Platform Magnetometers for Space Weather Monitoring

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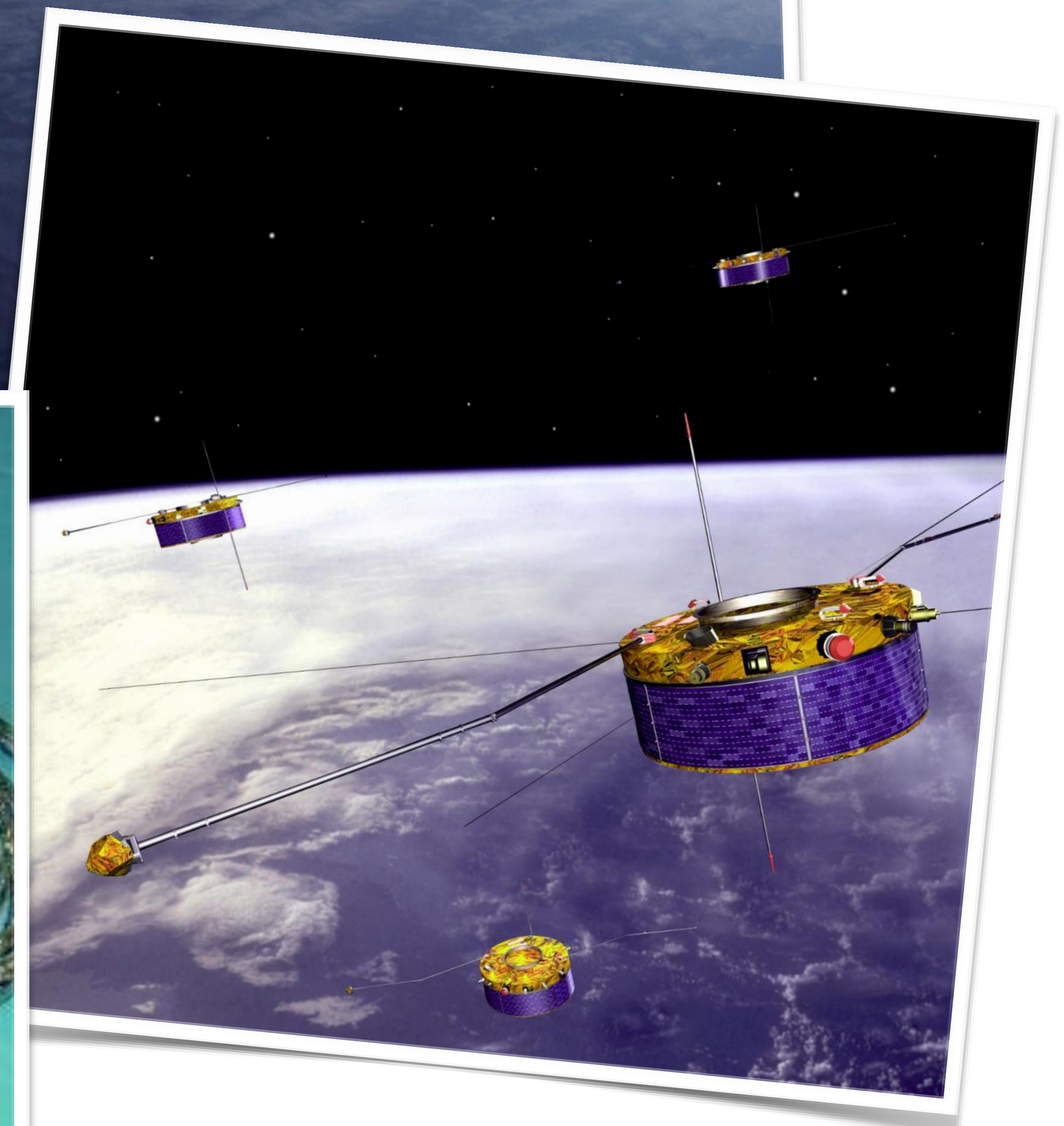
ESA special thanks: Rune Floberghagen, Björn Frommknecht, Paul McNamara, Ian Harrison, Berta Hoyos

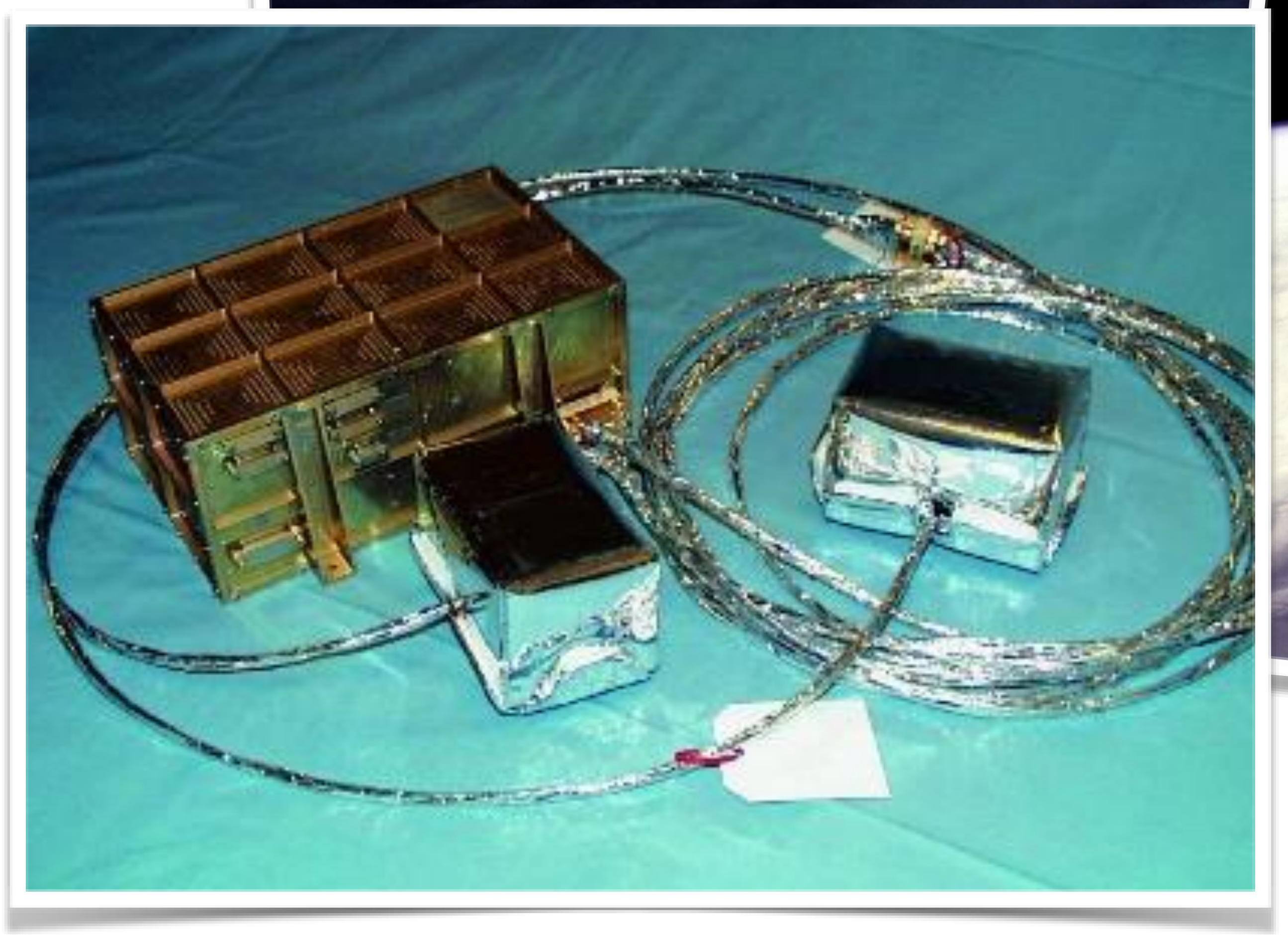
Background

- Magnetometers are fundamental space science and space weather instruments (and used in solid Earth & planetary sciences as well).
- Traditionally ‘scientific magnetometers’ are placed on booms, away from stray field sources originating inside the spacecraft.

ESA / AOES Medialab

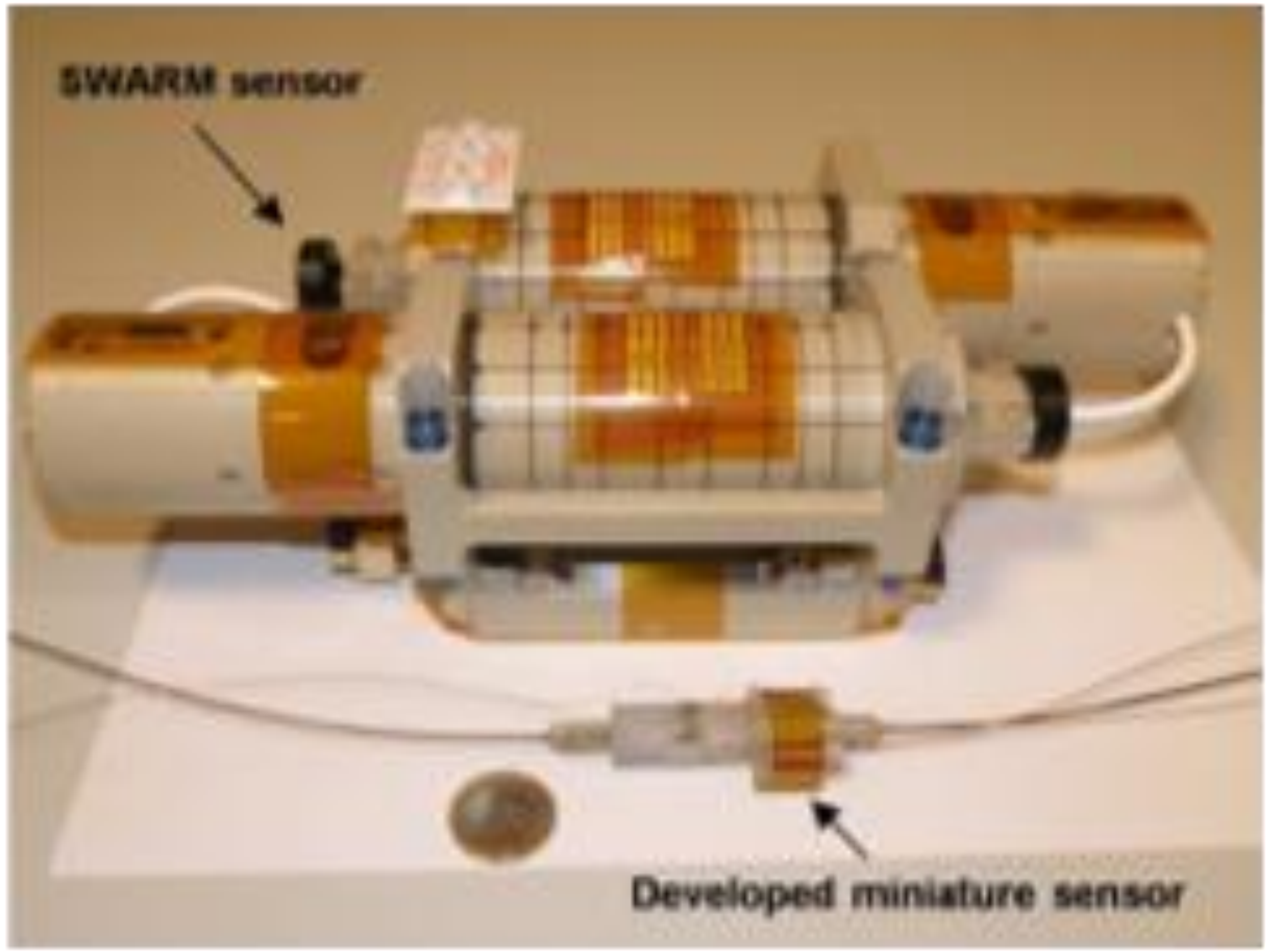


ESA

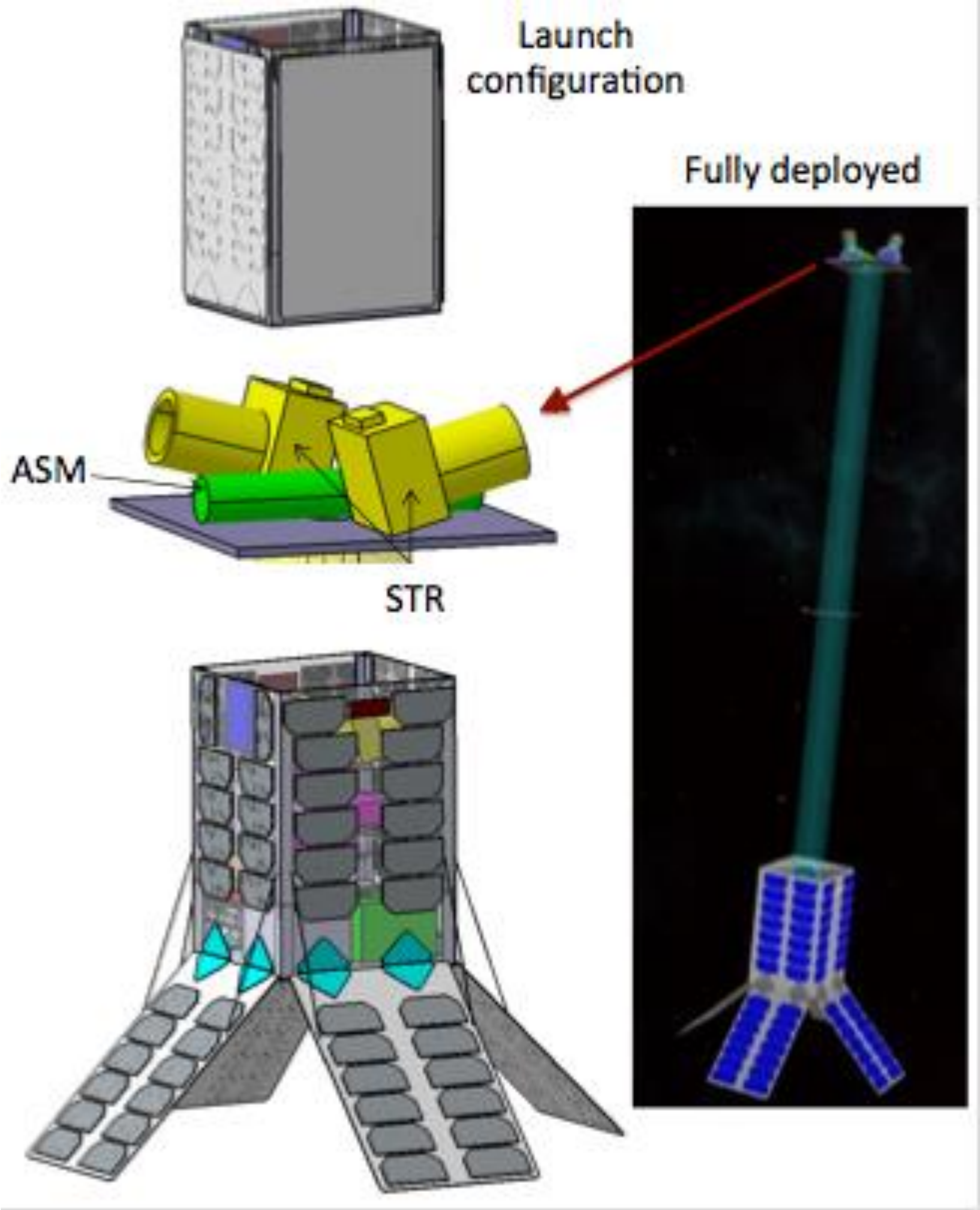


Imperial College London

Miniaturised science magnetometers



Rutkowski et al., Sensors and Actuators, 2014



Hulot, IAGA, 2017
Nanomagsat (12u)

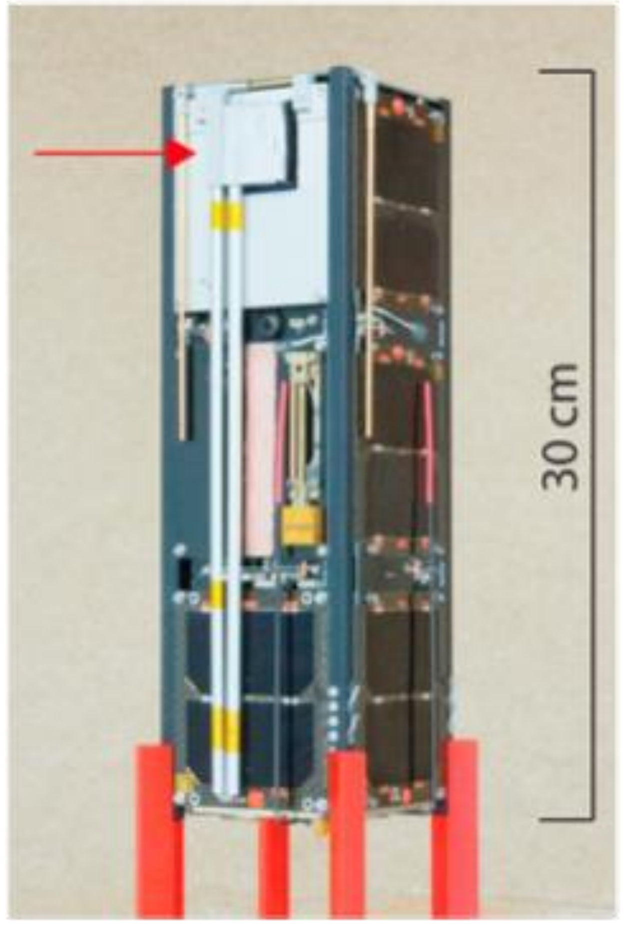
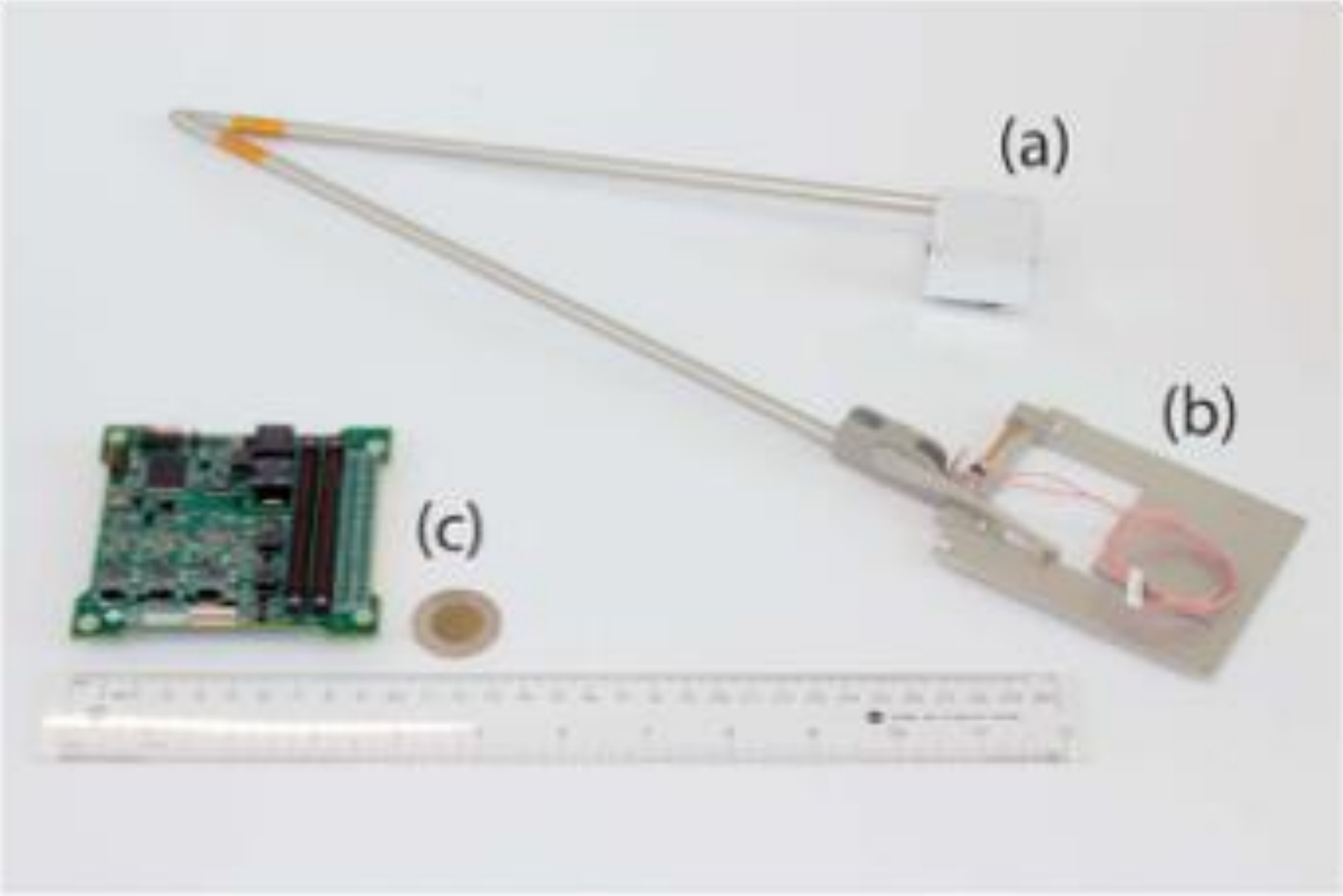


Figure 1. Miniature boom-mounted fluxgate magnetometer sensor stowed on the Ex-Alta 1 CubeSat. The arrow shows the fluxgate sensor atop its folding 60 cm boom in its stowed configuration.



Miles et al., JGR Space Physics, 2016
Ex-Alta 1 (QB50)

Platform magnetometers

- Magnetometers are also an essential part of the attitude control subsystem on many low Earth orbiting satellites.

- Sentinels and Earth Explorer missions typically use three hot redundant fluxgate magnetometers from manufacturers Billingsley, Zarm Technik and LusoSpace for this purpose.

Billingsley, magnetometers.com

Zarm Technik

LusoSpace

Measurement requirements for space weather

Application	Suitable orbit types	Signal	Time scale / required sampling
Interplanetary Magnetic Field	Sun-Earth L1	5-25 nT	1 minute
Ionospheric and magnetospheric currents	LEO	10-1000 nT	4 seconds
Geomagnetic pulsations	Any Earth orbit	1-20 nT	1-600 seconds
Magnetopause crossings	Geostationary and highly eccentric Earth orbits	10-20 nT	1 minute

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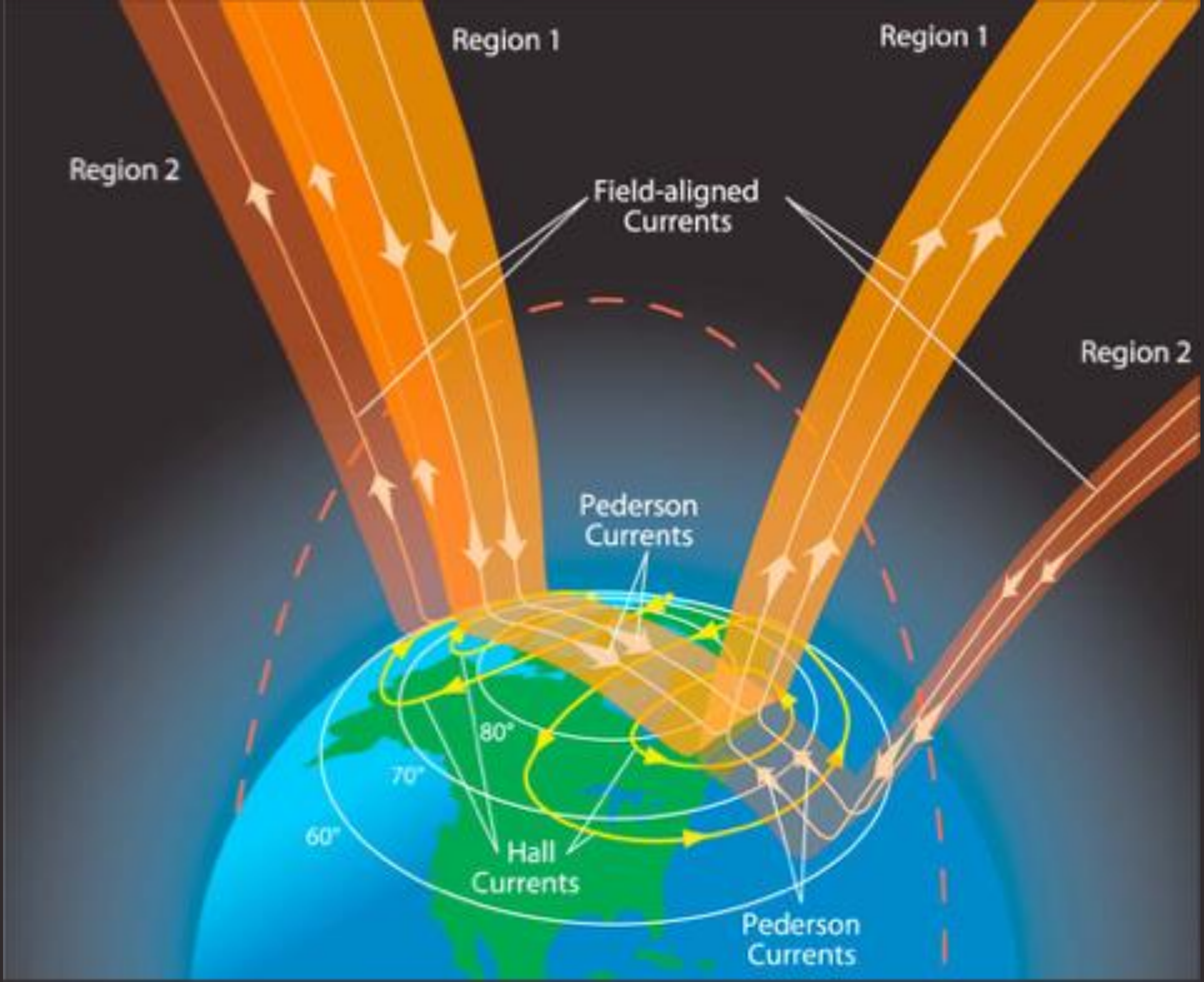
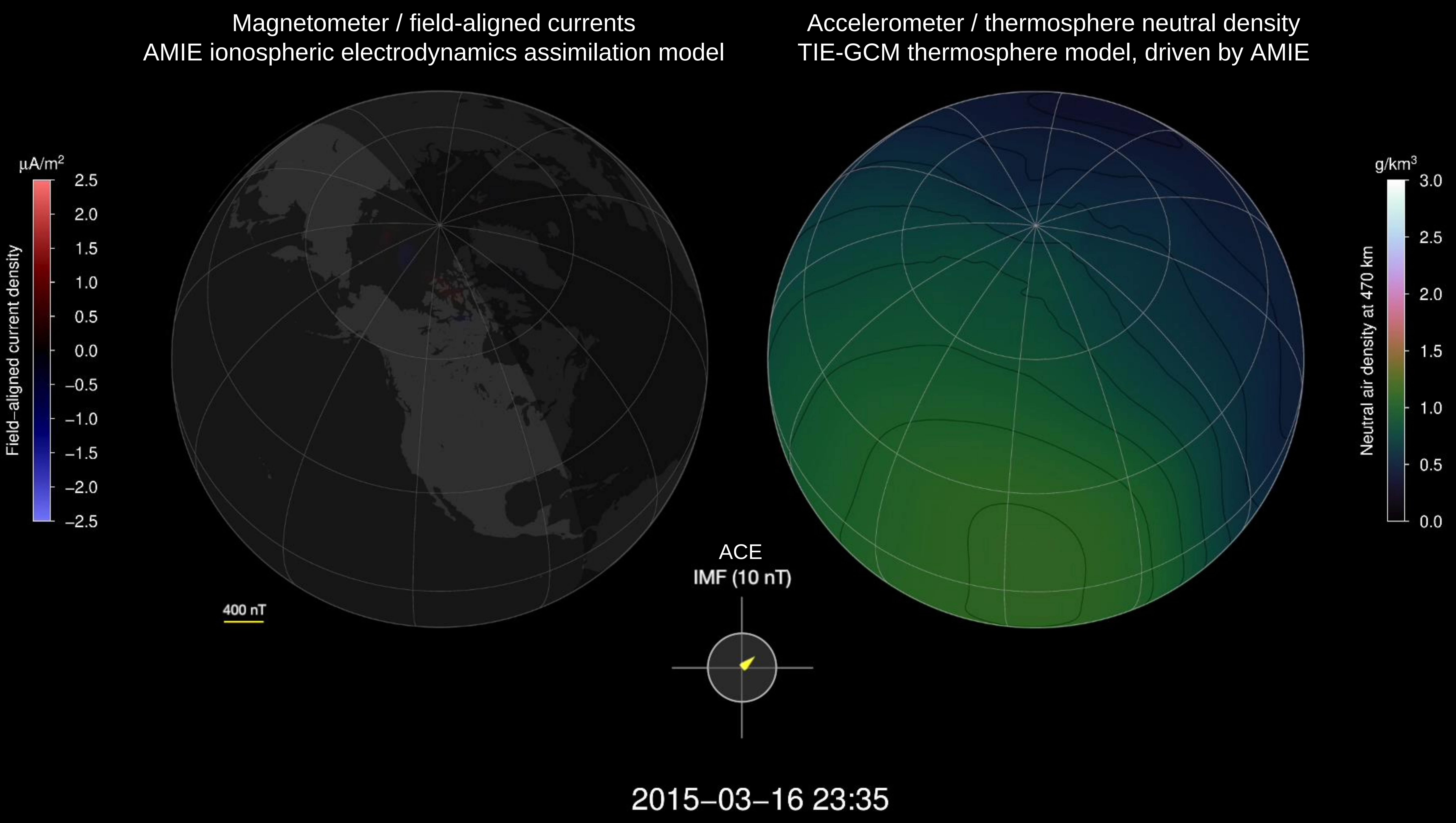

Region 1
Region 1
Region 2
Field-aligned Currents
Region 2
Pederson Currents
80°
70°
60°
Hall Currents
Pederson Currents


Magnetometer / field-aligned currents
AMIE ionospheric electrodynamics assimilation model
Accelerometer / thermosphere neutral density
TIE-GCM thermosphere model, driven by AMIE
μA/m2
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Field−aligned current density
400 nT
ACE
IMF (10 nT)
g/km3
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Neutral air density at 470 km
2015−03−16 23:35

How can platform data from LEO satellites be applied for Space Weather?

1. For post-event analysis

2. For validating existing thermosphere-ionosphere models (climatological, semi-empirical and general circulation models)

3. As inputs for updating or creating new climatological and semi-empirical models

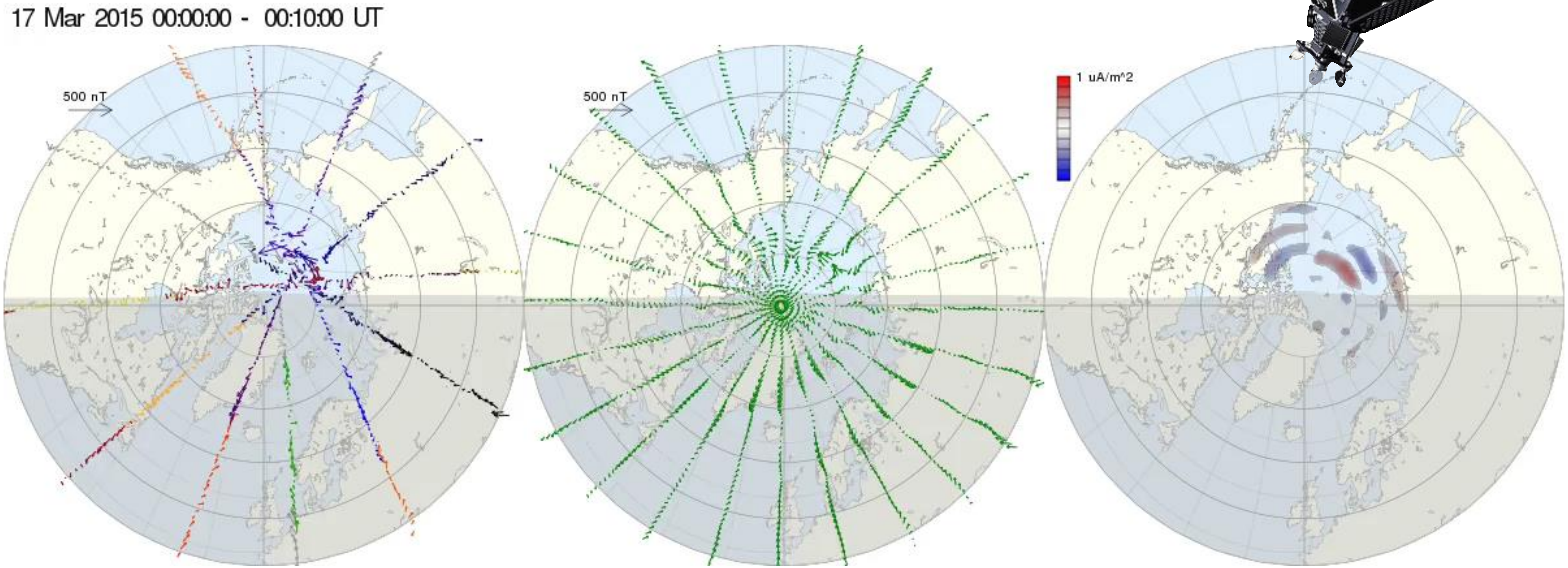
4. For data assimilation in (future) models, preferably with low latency and real-time

Inspiration: AMPERE / Iridium

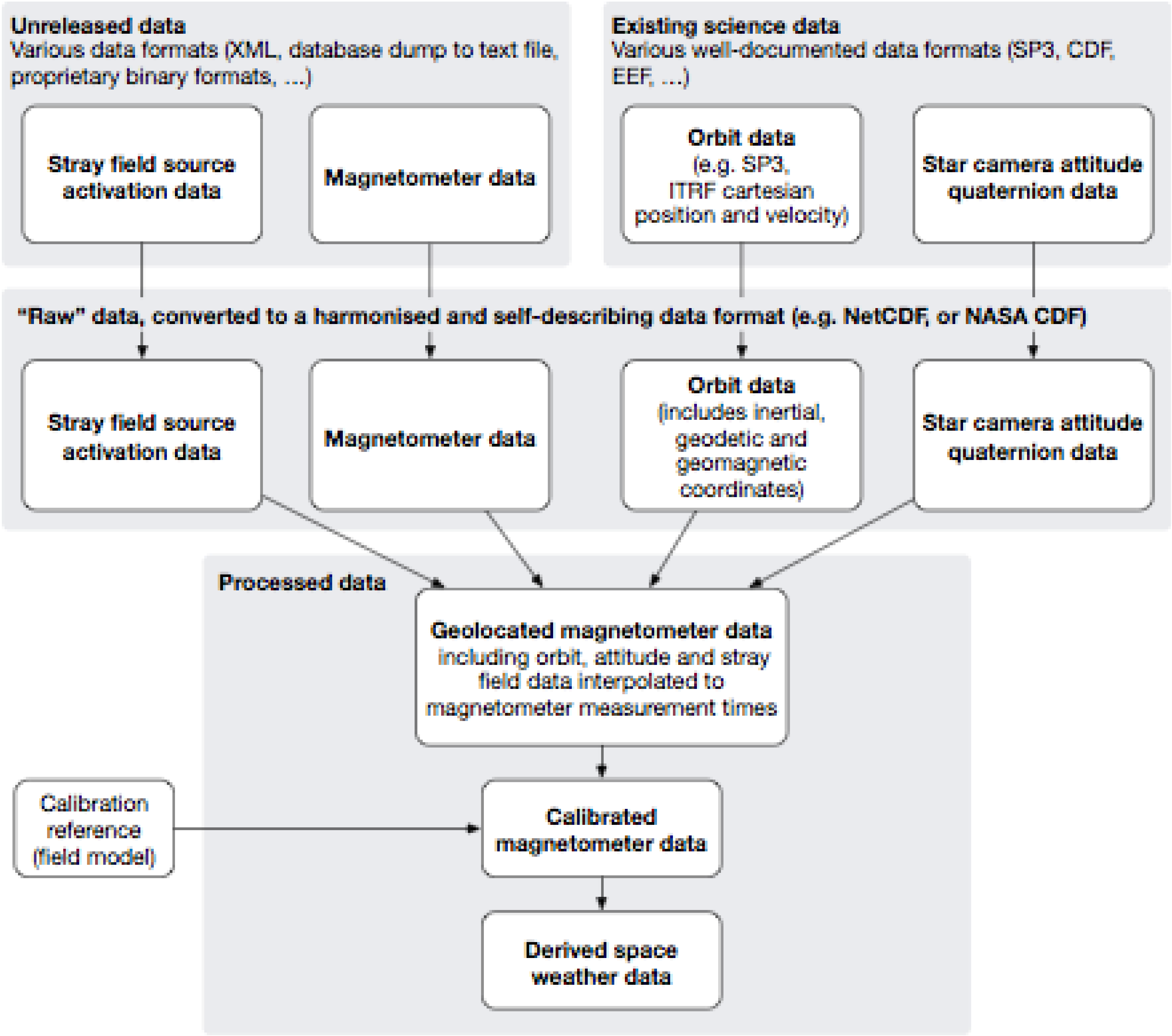

Lockheed Martin

66 satellites, 6 orbital planes, h = 780 km, i = 86.4 deg

http://ampere.jhuapl.edu



LEO satellite data flow



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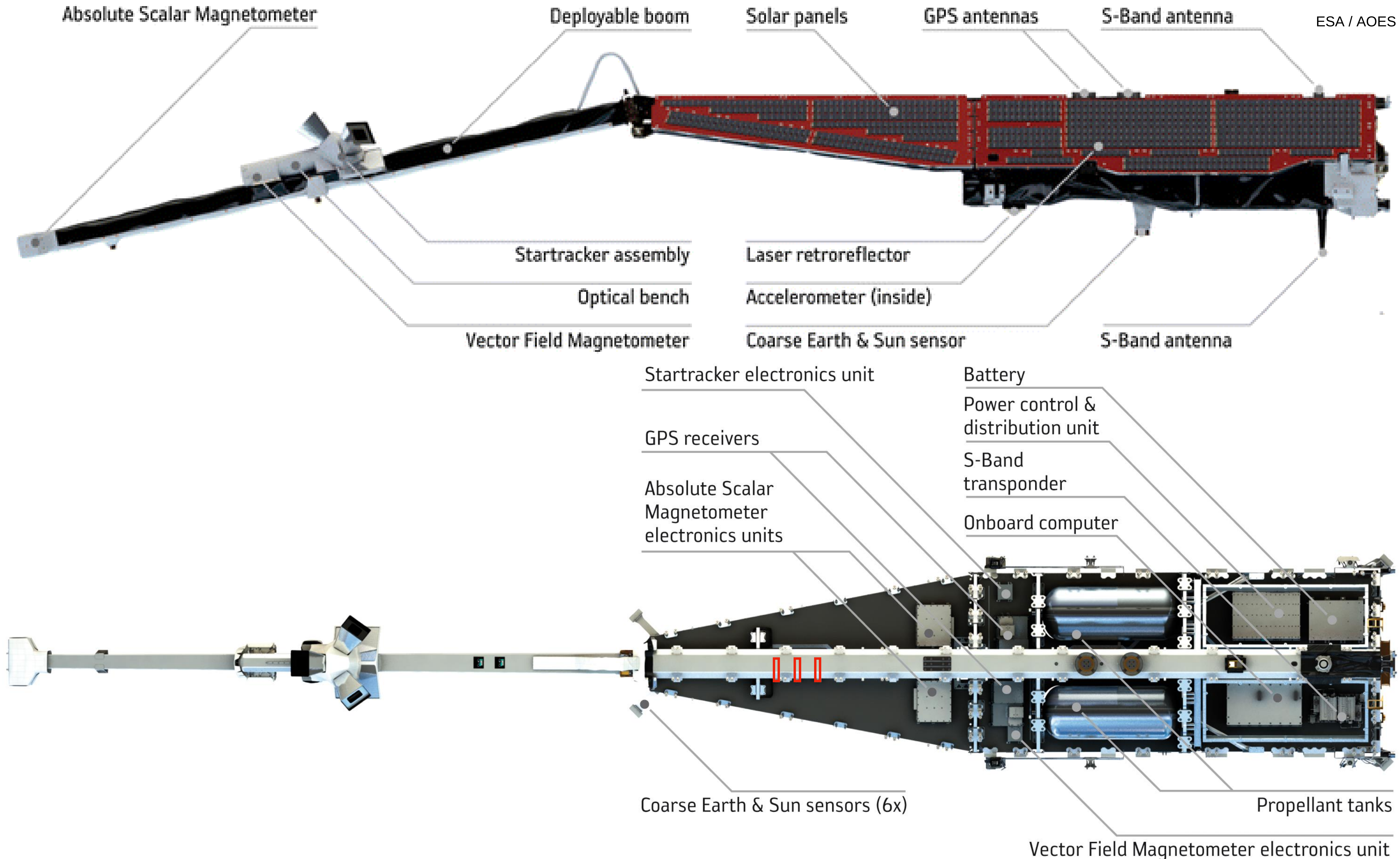


Methods - Algorithm 1

$\vec{B}$	:	Non-calibrated vector data in nT
$\vec{B_{ref}}$	:	Reference vector data (CHAOS 6 model) in nT
$\vec{E} = (e_1, e_2, e_3)$	:	Euler angles in degrees
A	:	Euler angle rotation matrix
$\vec{b} = (b_1, b_2, b_3)$	:	Offsets in nT
$\vec{s} = (s_1, s_2, s_3)$	:	Scale factors in nT/nT
$\vec{u} = (u_1, u_2, u_3)$	:	Misalignment angles in degrees

Following SW-RS-DSC-SY-0002, Issue 6.3 Swarm Level 1b Processor Algorithms

$$w = \sqrt{1 - \sin^2(u_2) - \sin^2(u_3)}$$

$$S^{-1} = \begin{pmatrix} 1/s_1 & 0 & 0 \\ 0 & 1/s_2 & 0 \\ 0 & 0 & 1/s_3 \end{pmatrix} \qquad P^{-1} = \begin{pmatrix} 1 & 0 & 0 \\ \sin(u_1)/\cos(u_1) & 1/\cos(u_1) & 0 \\ -(\sin(u_1)\sin(u_3)+\cos(u_1)\sin(u_2))/w\cos(u_1) & -\sin(u_3)/w\cos(u_1) & 1/w \end{pmatrix}$$

$$\vec{B_{ref}} = AP^{-1}S^{-1}(\vec{B} - \vec{b})$$

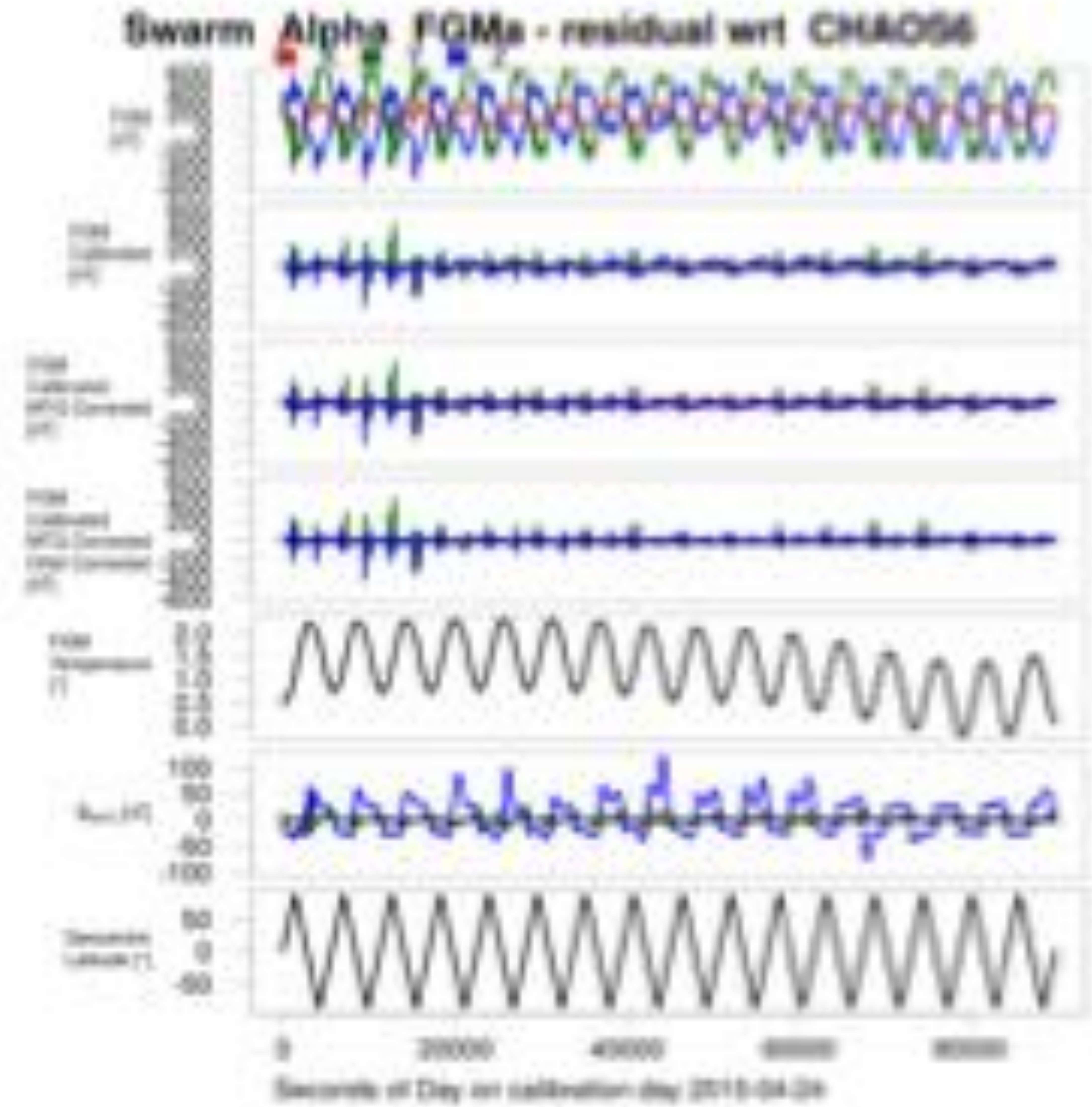
Solve for $\vec{b}$, S, P and A using least-square algorithm and apply to non-calibrated data.

$$\vec{B_{cal}} = AP^{-1}S^{-1}(\vec{B} - \vec{b})$$

Methods - Algorithm 2

1. Read input data
2. Apply time shift of 1.2 seconds on FGM data
3. Interpolate all data to Swarm L1b timestamps
4. Calculate MTQ impact on FGM using MTQ model
5. Calculate CHAOS6 model in NEC
6. Rotate all data into FGM RF (dB_MTQ, VFM, CHAOS6)
7. Apply negative MTQ impact on CHAOS6 data
8. Calibrate FGM using Vector-Vector calibration and CHAOS6 model
9. Apply MTQ impact on calibrated FGM
10. Remove orbital and half-orbital bandpass filter from FGM
11. Rotate FGM into NEC
12. Calculate residual wrt. CHAOS6
13. Write calibrated FGM into cdf files

Results - Calibration Steps



Median Absolute Deviation (MAD) of calibration residui wrt CHAOS6 on Swarm Alpha for applied calibration and characterization steps in nT. Comparison was done in FGMa's reference frame.

	dBx [nT]	dBy [nT]	dBz [nT]
FGMa wrt CHAOS6	104.94	442.07	274.54
FGMa calibrated wrt CHAOS6	57.20	15.01	40.91
FGMa calibrated MTQ corrected wrt CHAOS6	52.13	13.93	32.82
FGMa calibrated MTQ corrected orbit corrected wrt CHAOS6	23.36	9.97	17.78
VFM wrt CHAOS6	5.89	10.43	9.24

Results - Calibration Parameters Overview

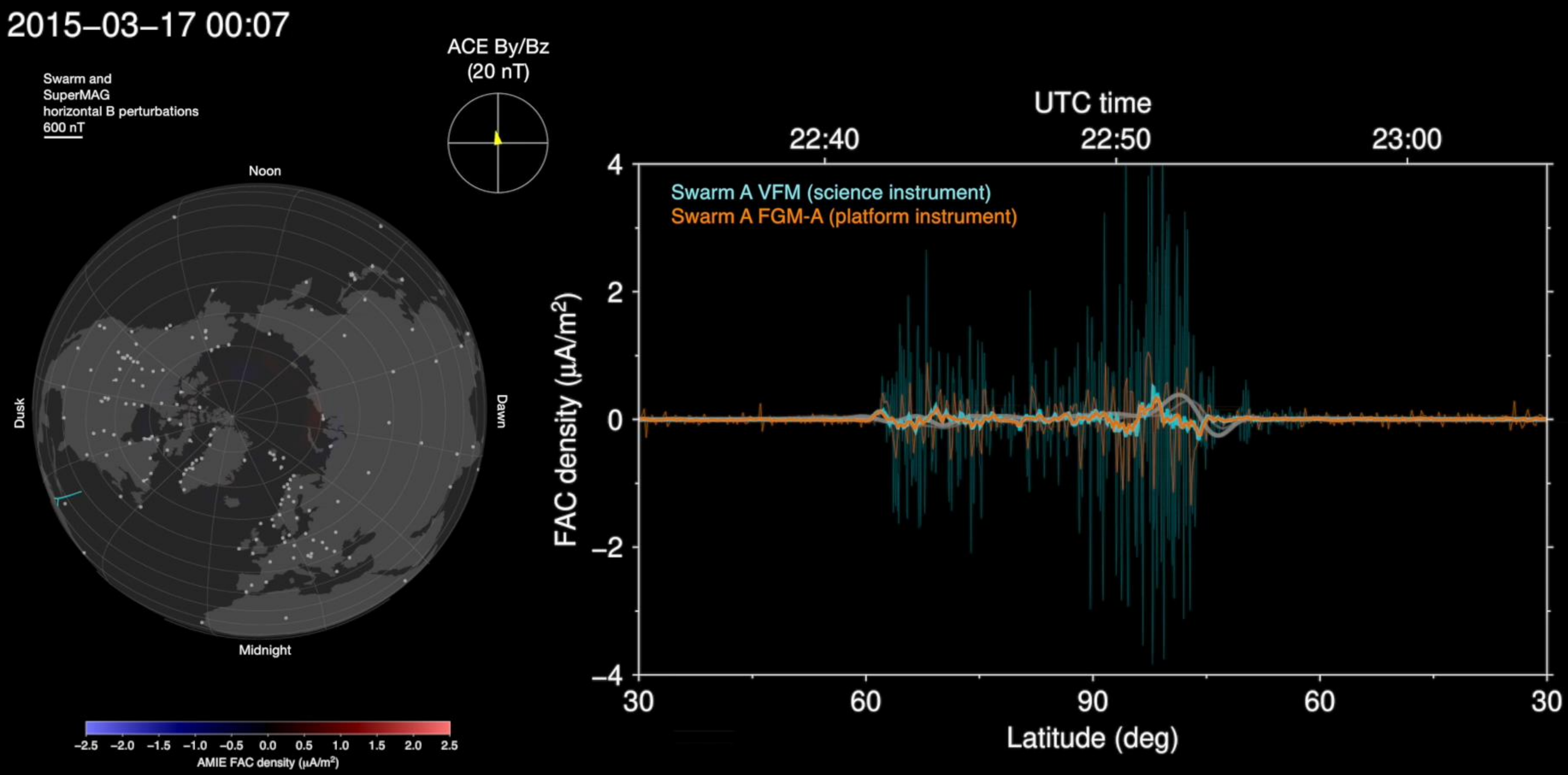
	Swarm Alpha			Swarm Bravo			Swarm Charlie		
	FGM A	FGM B	FGM C	FGM A	FGM B	FGM C	FGM A	FGM B	FGM C
b1	169.89	177.40	81.65	-101.86	-148.74	-272.94	-22.96	120.41	-123.89
b2	232.41	228.34	205.85	-153.06	-26.54	76.33	65.45	96.95	69.45
b3	128.73	178.73	159.09	29.61	40.62	7.73	34.28	-64.42	133.72
s1	0.998990	0.999272	1.000061	0.996583	0.996715	0.997482	0.997790	0.998458	0.998612
s2	0.998676	0.998325	0.998553	0.997121	0.996407	0.996955	0.997468	0.998349	0.997190
s3	0.998638	0.998924	0.999165	0.996674	0.999548	0.995872	0.997124	0.997348	0.998559
u1	-0.5076	-0.6945	-0.5788	-0.5076	-0.6087	-0.5695	-0.4808	-0.5047	-0.3676
u2	-0.3175	-0.0060	-0.2054	-0.0282	0.2041	-0.6698	0.3423	-0.4736	-0.3917
u3	-0.3252	0.0495	0.3320	-0.1383	0.7913	-0.1344	-0.7767	0.4286	0.5601
e1	-0.3233	-0.4906	-0.7320	0.2525	-0.5904	0.8634	0.6460	-1.3820	-0.5852
e2	0.0572	0.4427	0.1543	0.6452	0.2072	0.1129	0.4462	-0.1262	0.4946
e3	0.0443	-0.2963	-0.2220	-0.5469	-0.3896	-0.1452	-0.1486	-0.0639	-0.3598

b: Offset [nT]
s: Scale Factor [nT/nT]
u: Misalignment Angle [degrees]
e: Euler Angle [degrees]

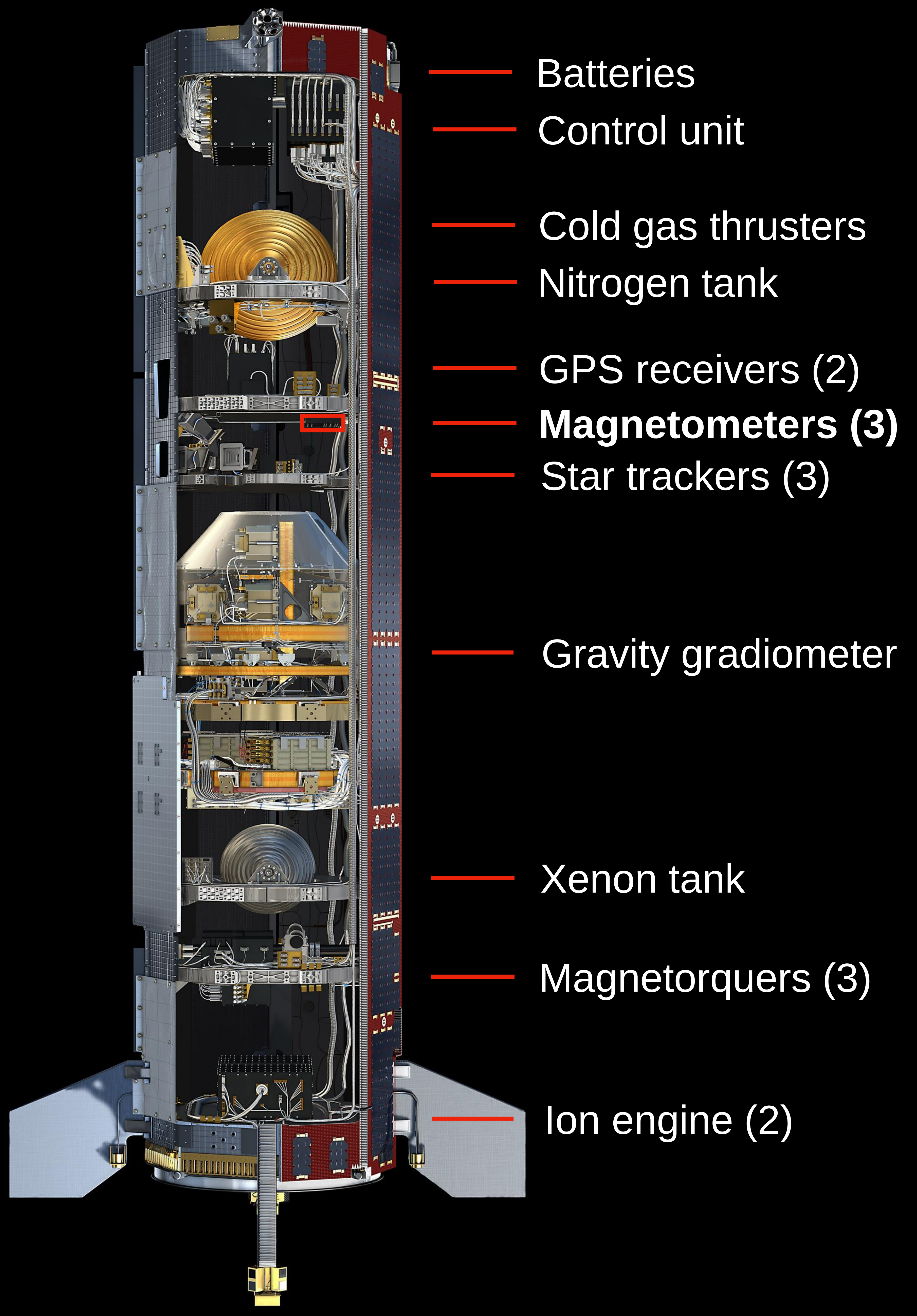
All estimated parameters are within the expected range

GFZ

HELMHOLTZ


2015–03–17 00:07
Swarm and
SuperMAG
horizontal B perturbations
600 nT
ACE By/Bz
(20 nT)
Noon
Dusk
Dawn
Midnight
−2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5
AMIE FAC density (μA/m²)
UTC time
22:40
22:50
23:00
Swarm A VFM (science instrument)
Swarm A FGM-A (platform instrument)
FAC density (μA/m²)
4
2
0
−2
−4
30
60
90
60
30
Latitude (deg)

GOCE



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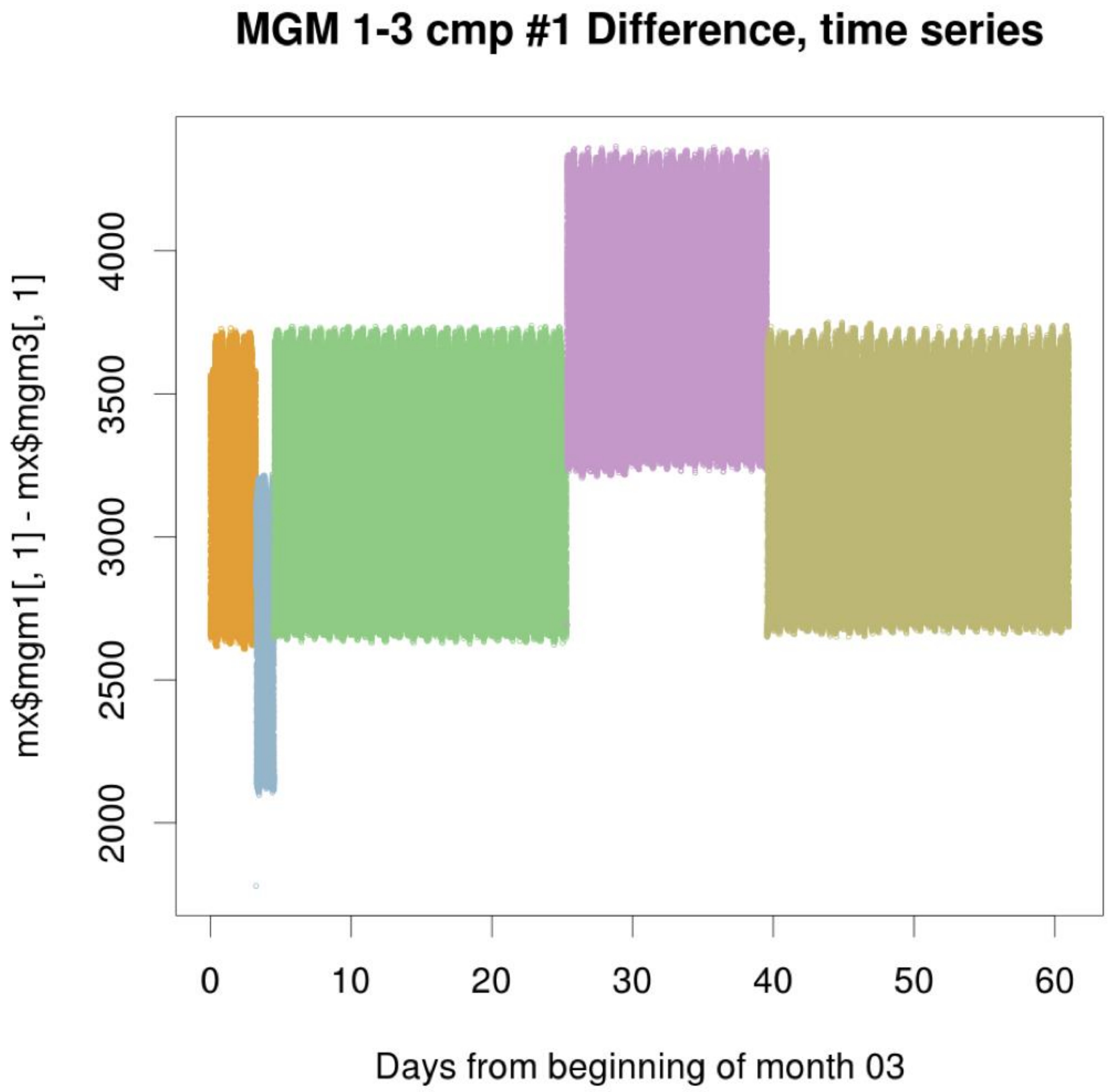
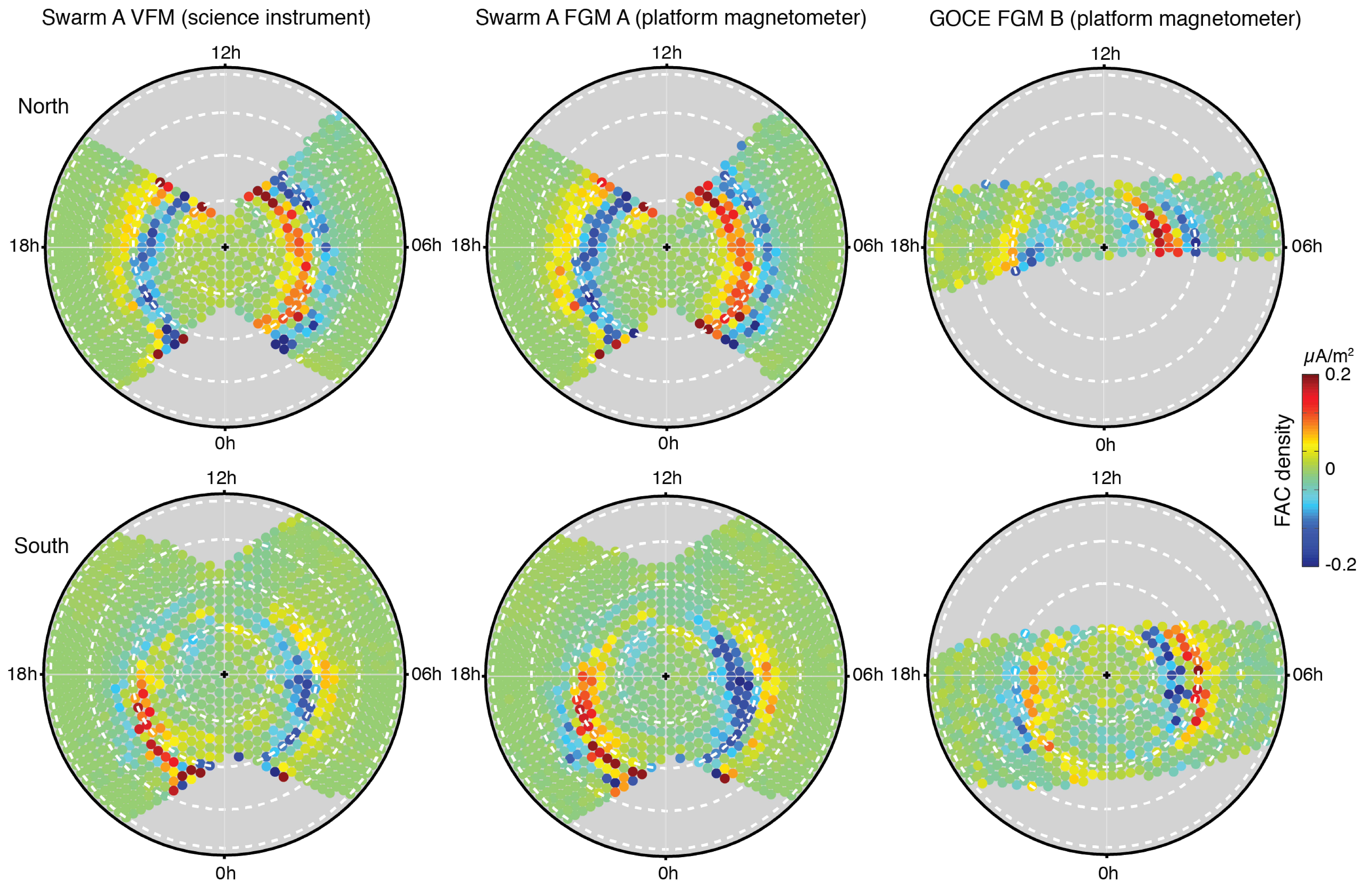
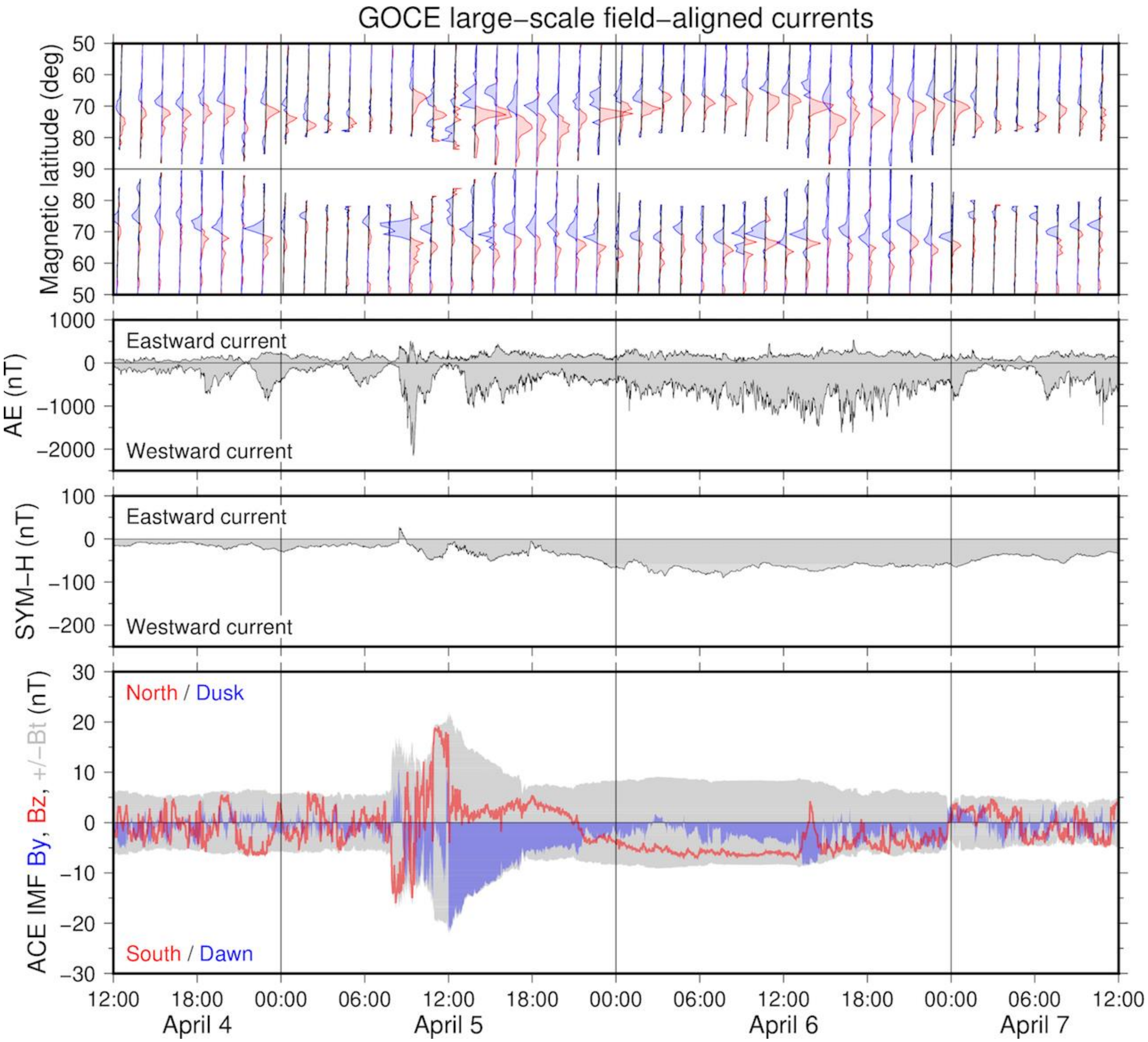
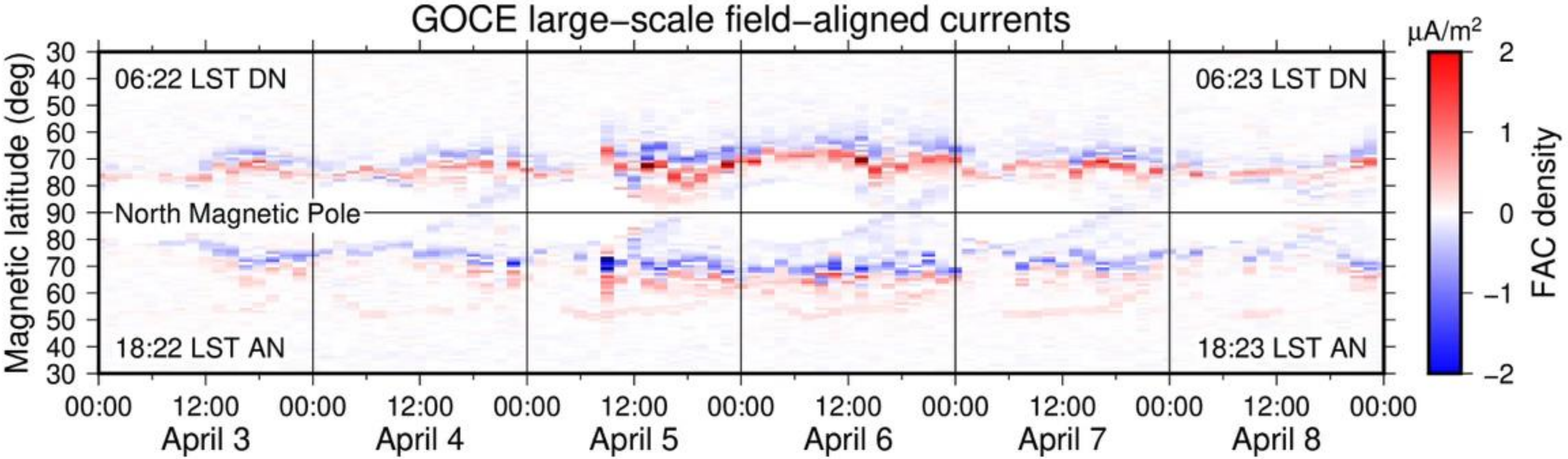

MGM 1-3 cmp #1 Difference, time series
mx$mgm1[, 1] - mx$mgm3[, 1]
2000
2500
3000
3500
4000
0
10
20
30
40
50
60
Days from beginning of month 03



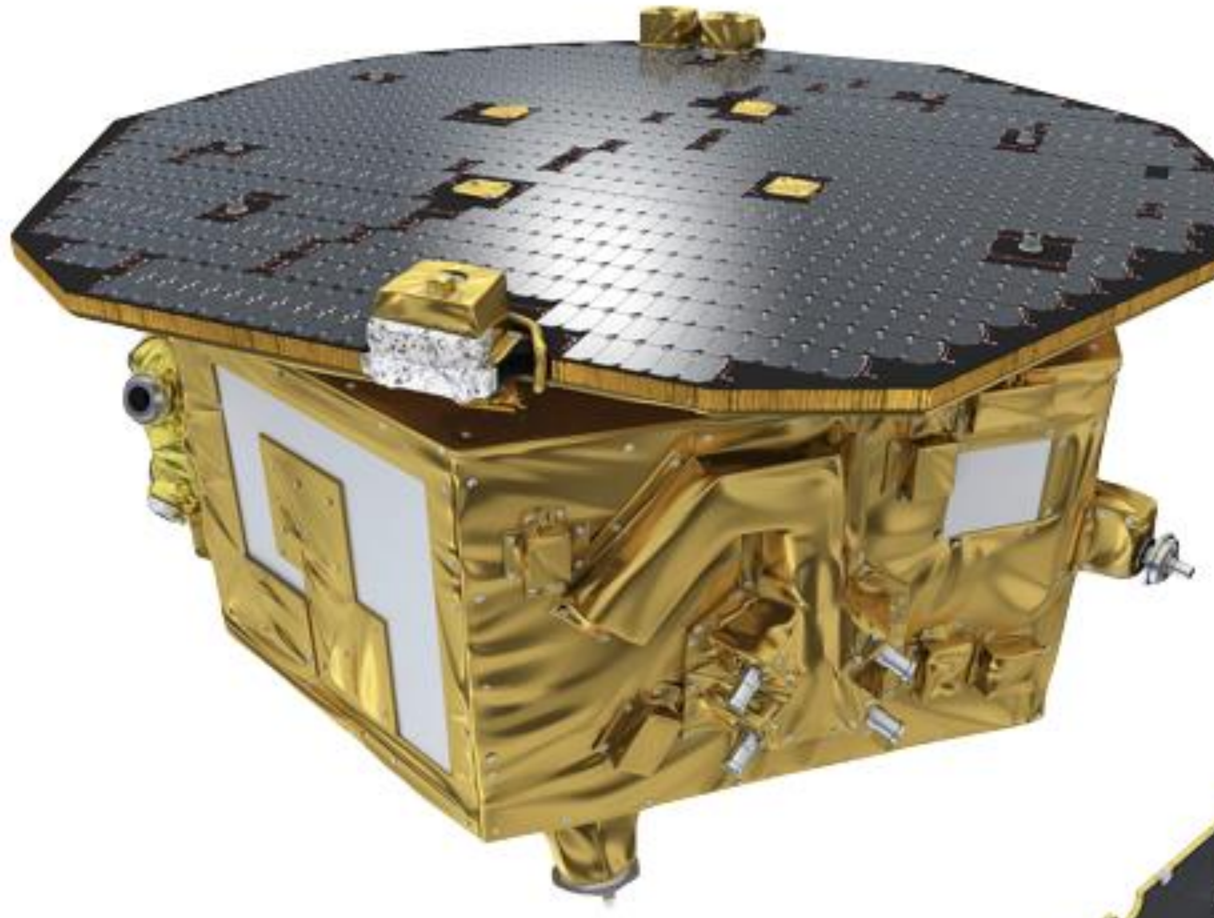
Swarm A VFM (science instrument)
Swarm A FGM A (platform magnetometer)
GOCE FGM B (platform magnetometer)
North
South
12h
18h
06h
0h
μA/m²
0.2
0
-0.2
FAC density

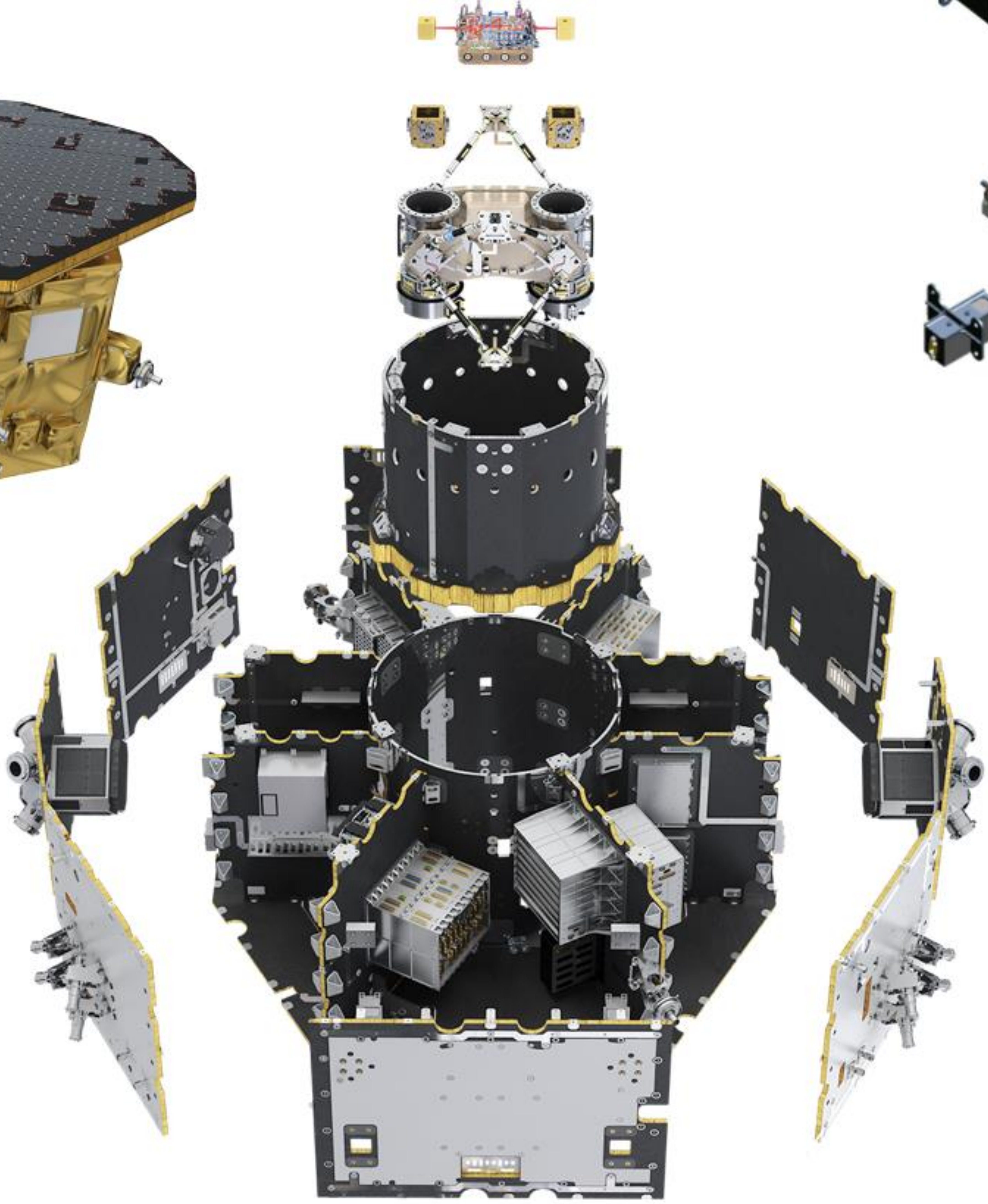


GOCE large−scale field−aligned currents
Magnetic latitude (deg)
50
60
70
80
90
80
70
60
50
1000
0
−1000
−2000
AE (nT)
Eastward current
Westward current
100
0
−100
−200
SYM−H (nT)
Eastward current
Westward current
30
20
10
0
−10
−20
−30
ACE IMF By, Bz, +/−Bt (nT)
North / Dusk
South / Dawn
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
April 4
April 5
April 6
April 7

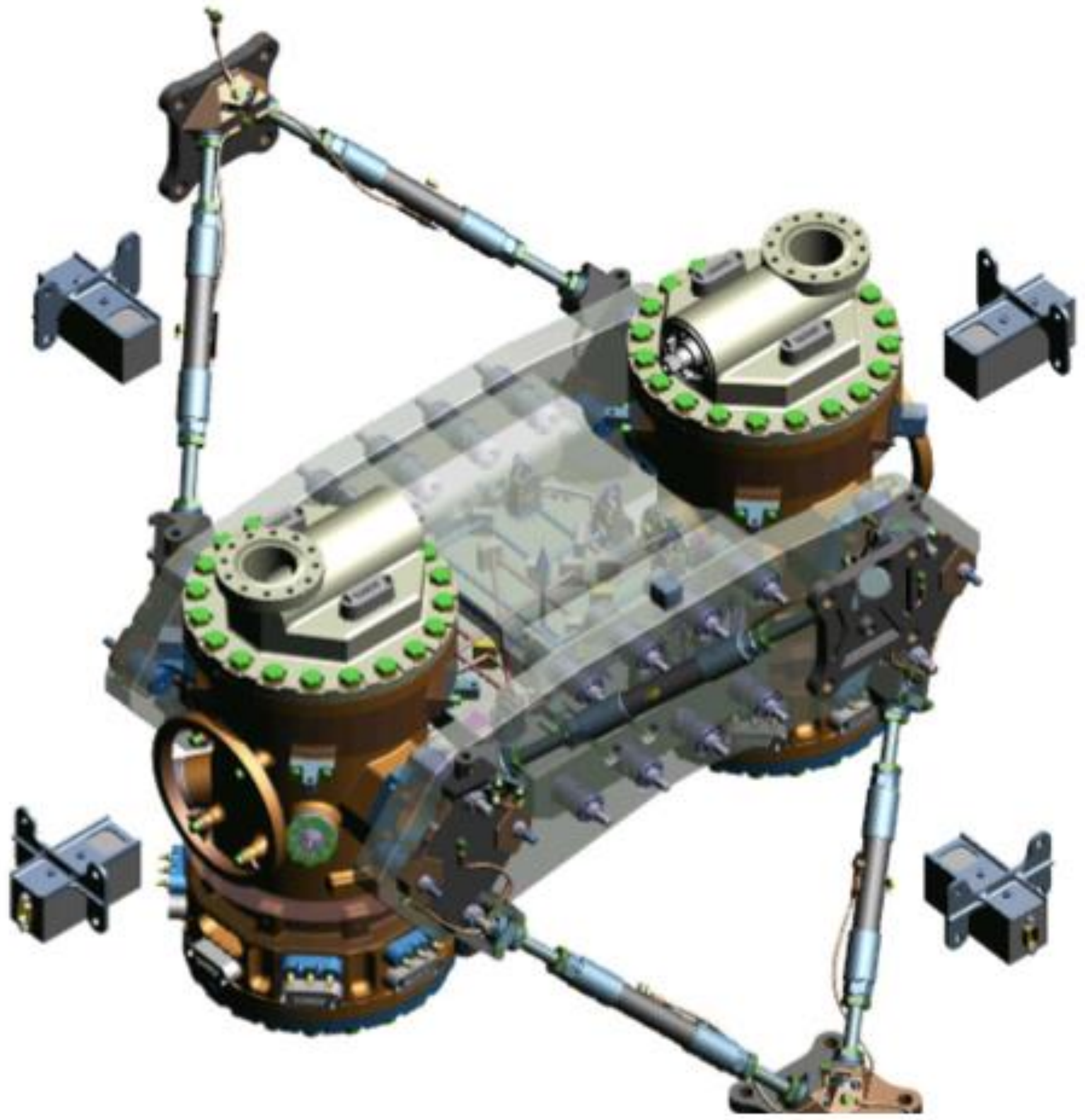

GOCE large−scale field−aligned currents
Magnetic latitude (deg)
30
40
50
60
70
80
90
80
70
60
50
40
30
06:22 LST DN
06:23 LST DN
North Magnetic Pole
18:22 LST AN
18:23 LST AN
00:00
12:00
00:00
12:00
00:00
12:00
00:00
12:00
00:00
12:00
00:00
12:00
00:00
April 3
April 4
April 5
April 6
April 7
April 8
μA/m²
2
1
0
−1
−2
FAC density

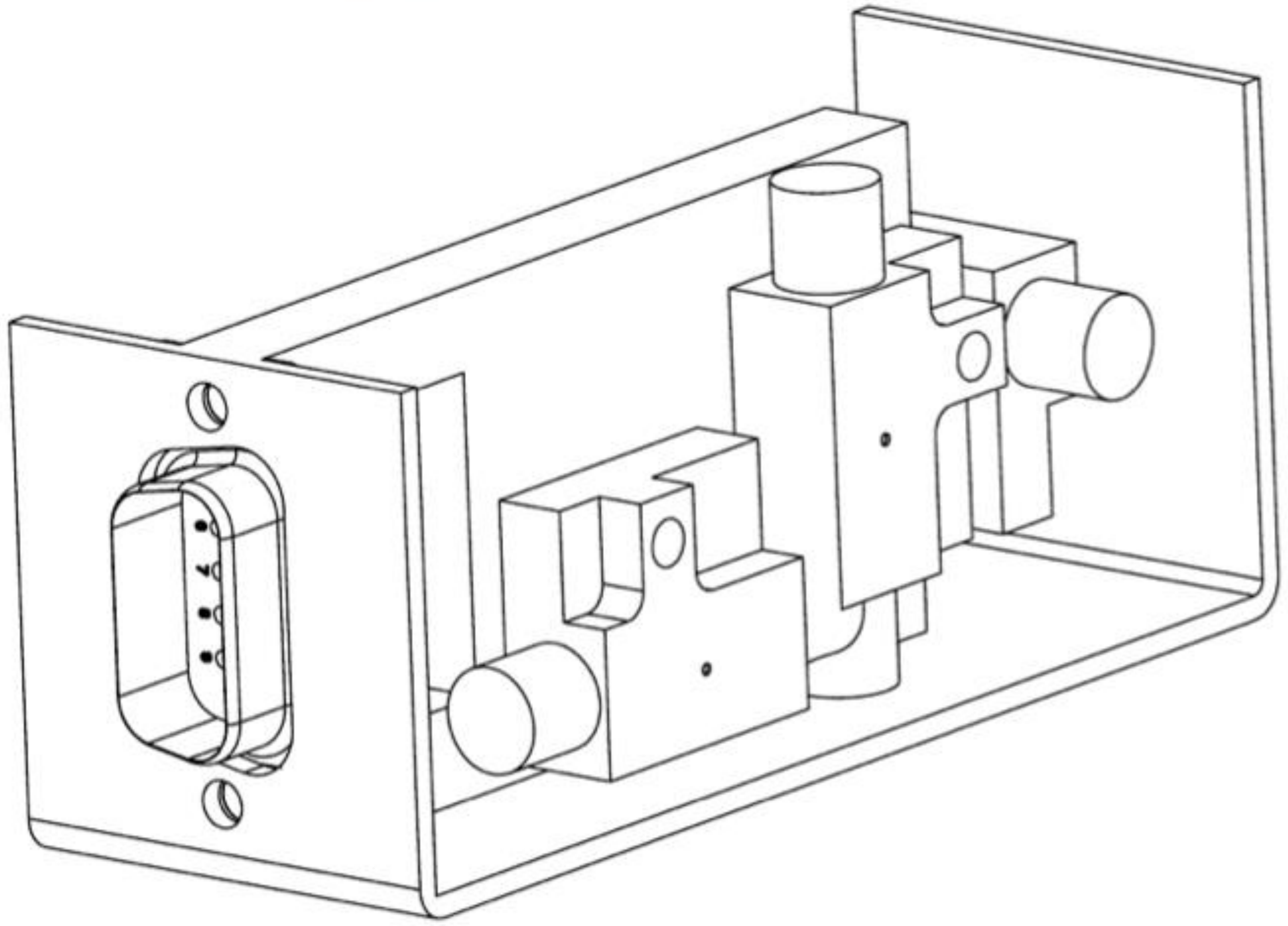
LISA Pathfinder



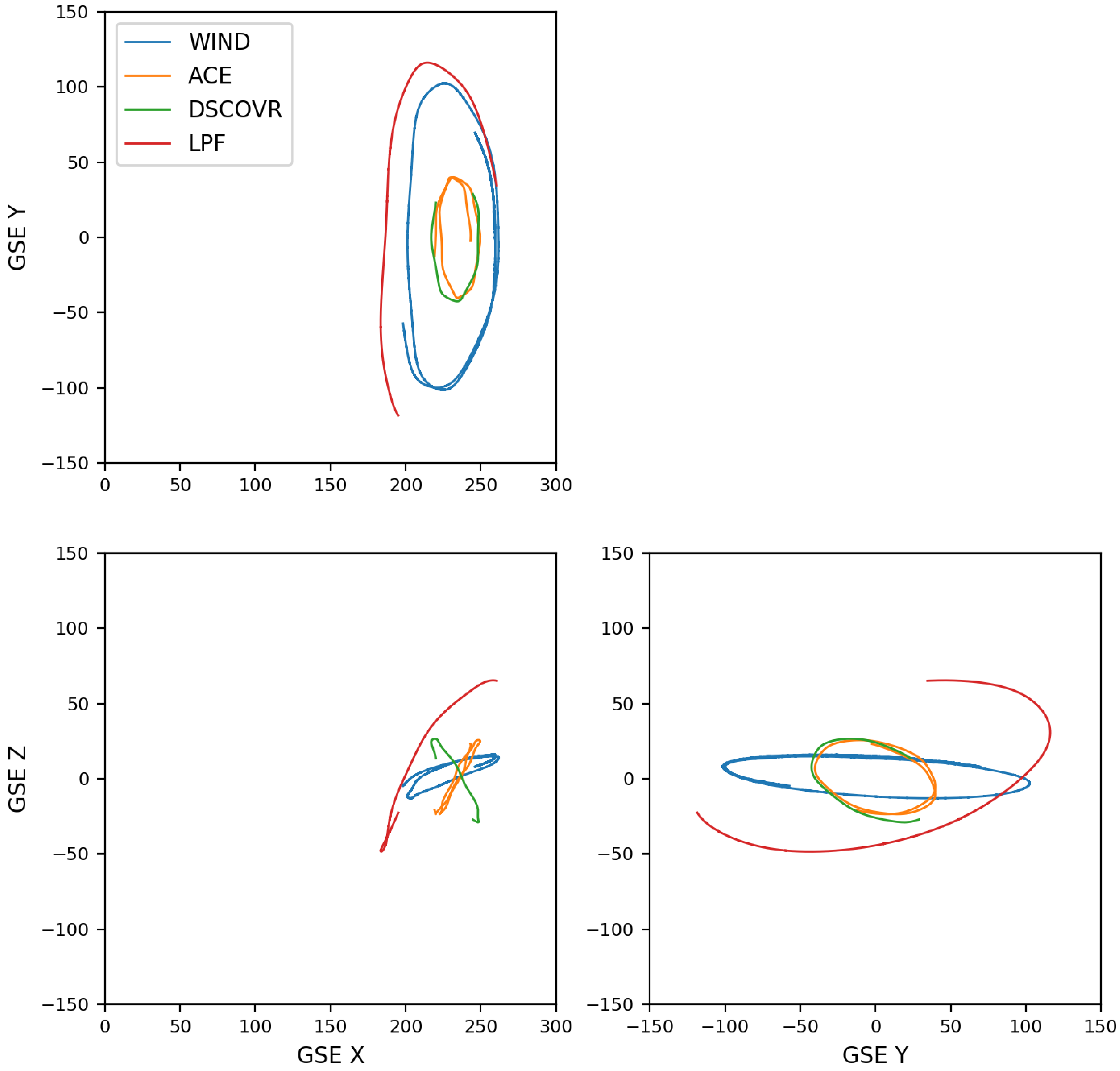


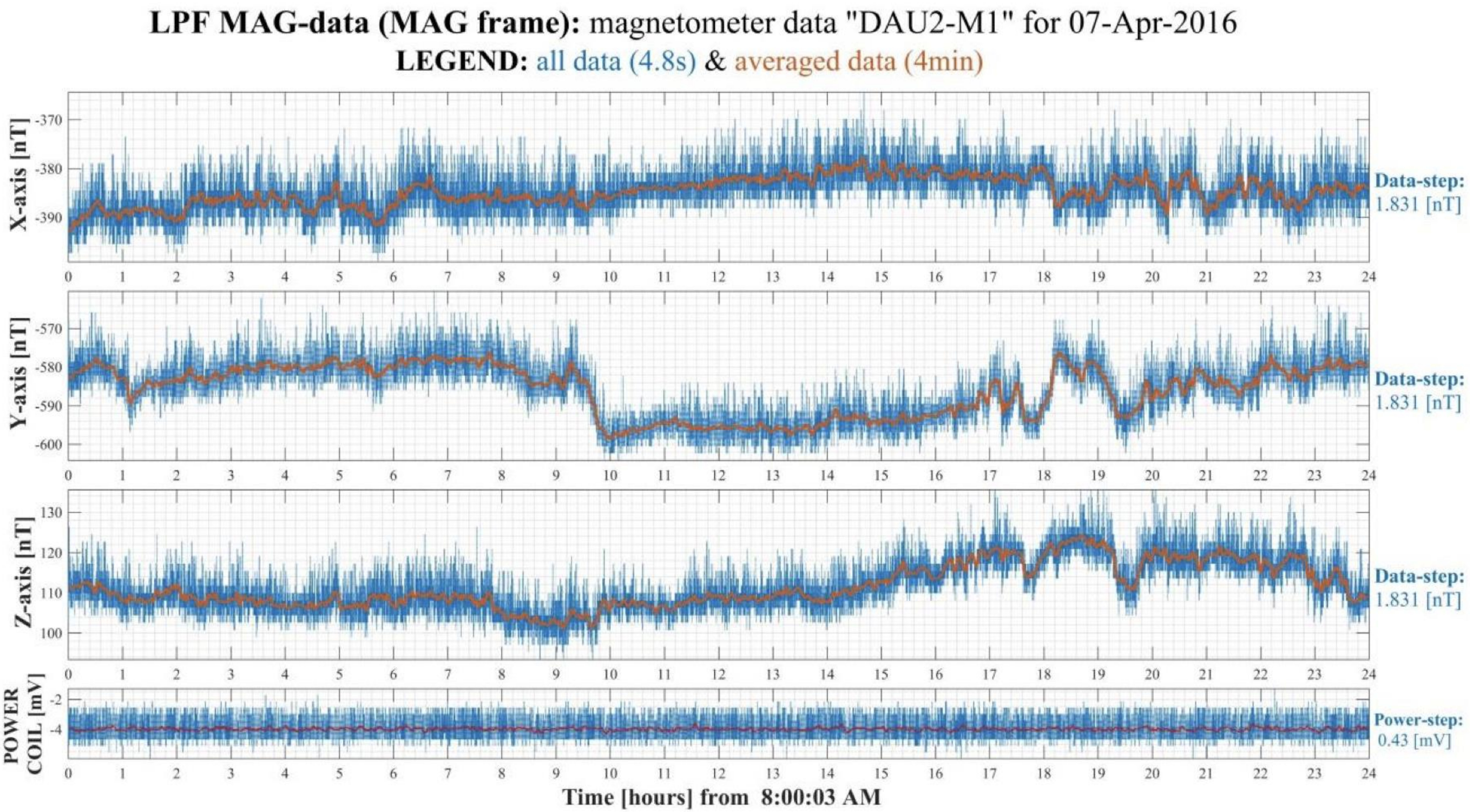
ESA / ATG Medialab



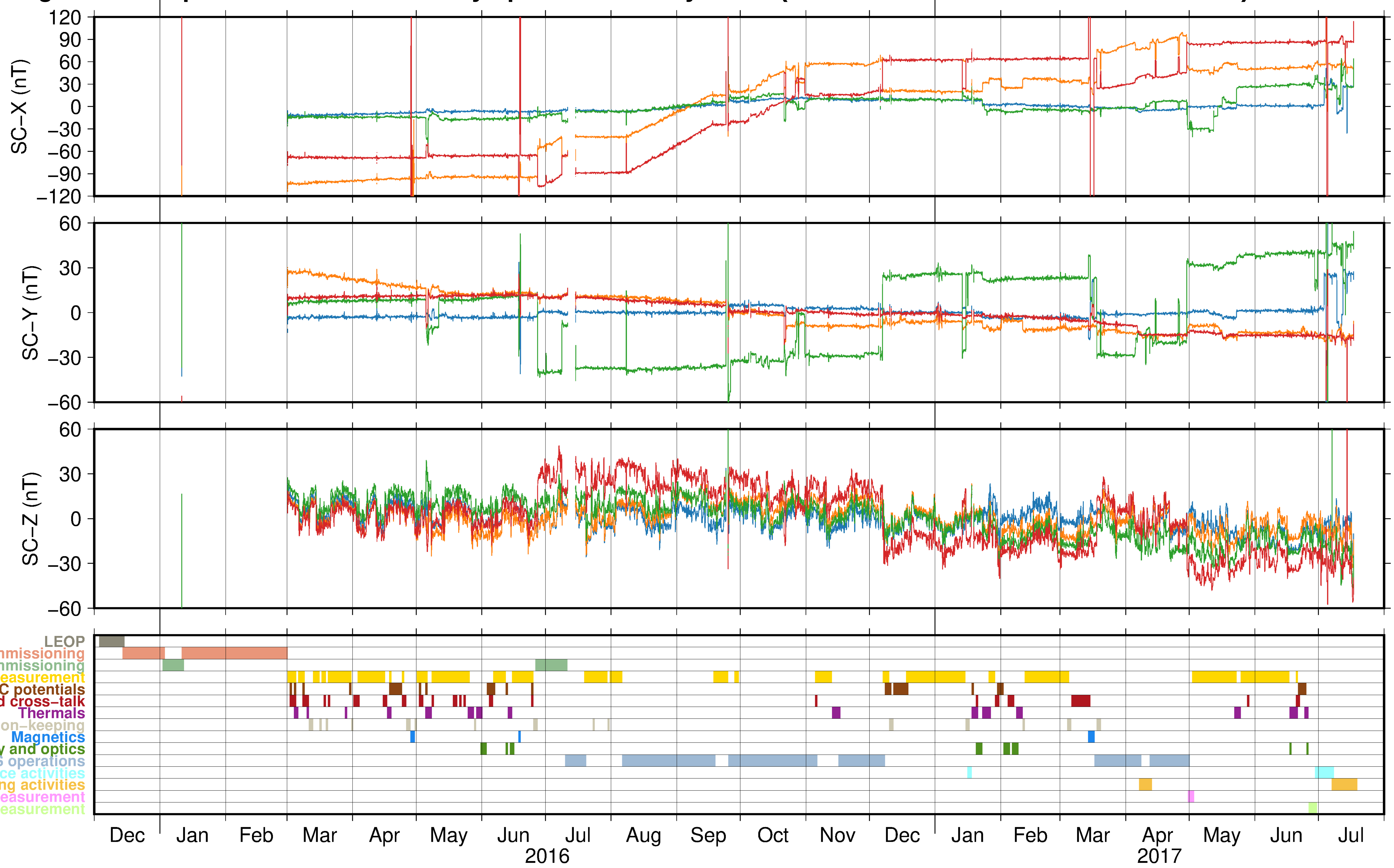


Billingsley TFM100G4-S

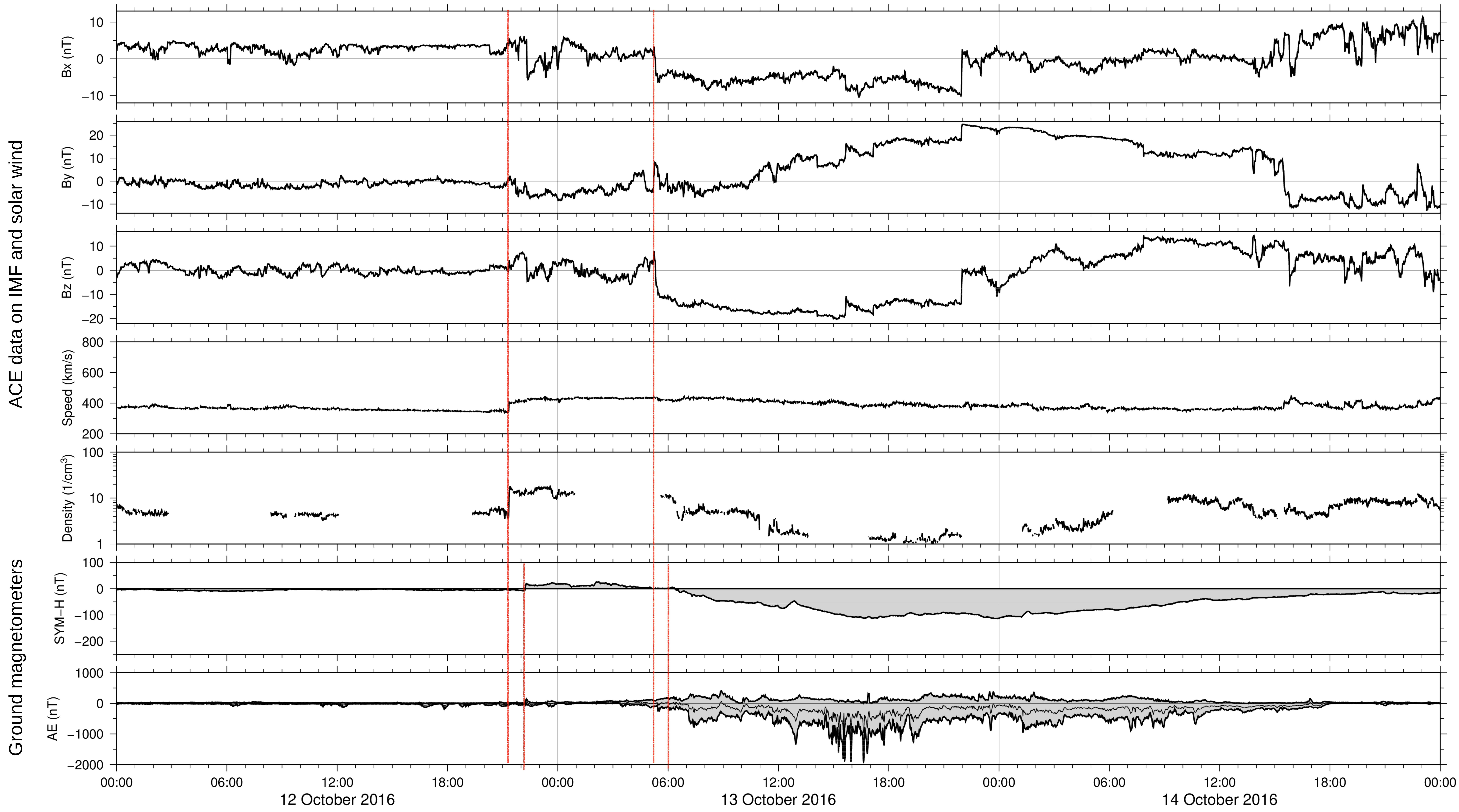

WIND
ACE
DSCOVR
LPF
GSE Y
GSE Z
GSE X
GSE Y
150
100
50
0
−50
−100
−150
0
50
100
150
200
250
300


LPF MAG-data (MAG frame): magnetometer data "DAU2-M1" for 07-Apr-2016
LEGEND: all data (4.8s) & averaged data (4min)
X-axis [nT]
Data-step: 1.831 [nT]
Y-axis [nT]
Data-step: 1.831 [nT]
Z-axis [nT]
Data-step: 1.831 [nT]
POWER COIL [mV]
Power-step: 0.43 [mV]
Time [hours] from 8:00:03 AM

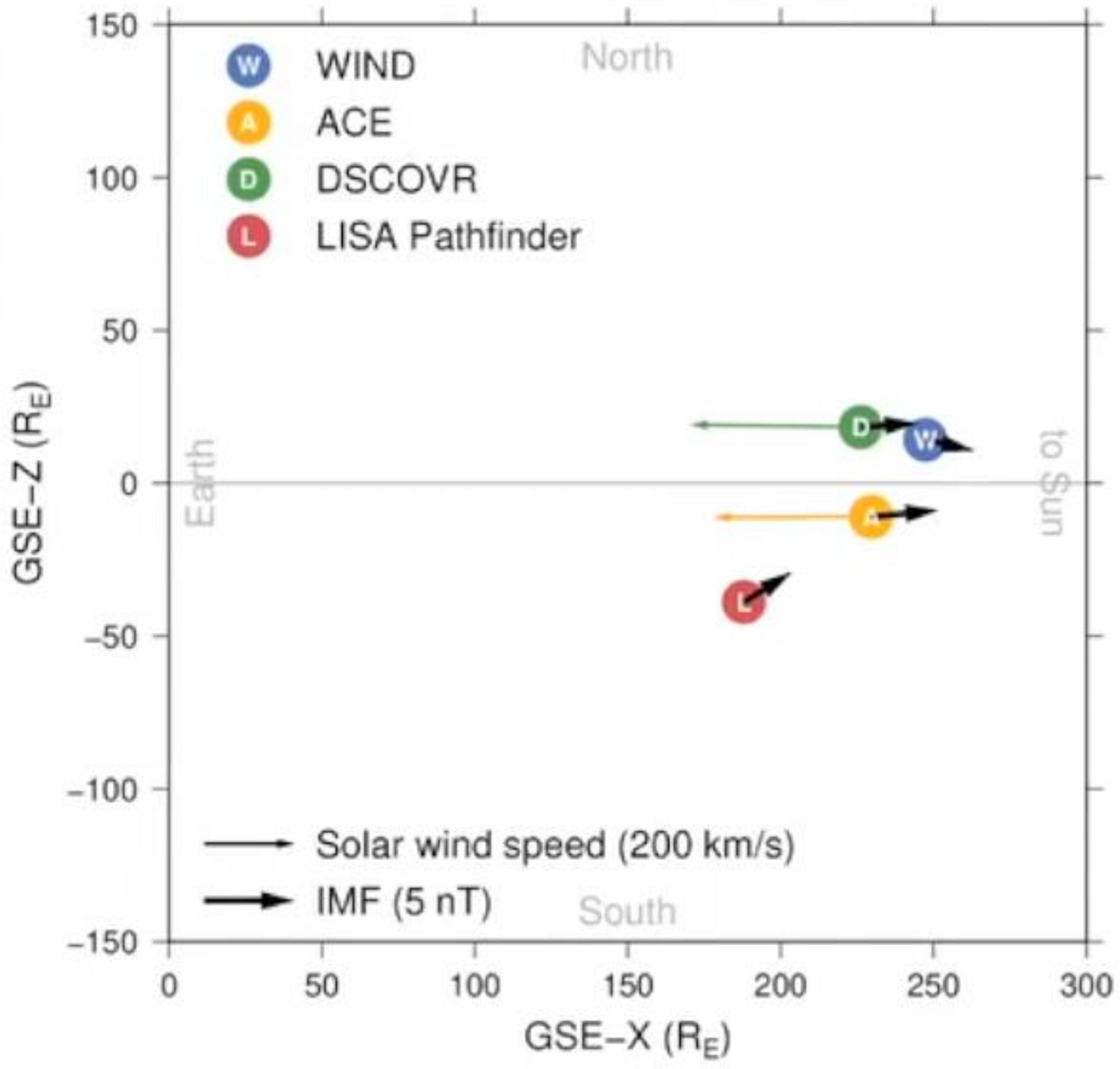
LISA pathfinder magnetometer perturbations induced by spacecraft subsystems (calibration curves based on ACE data)

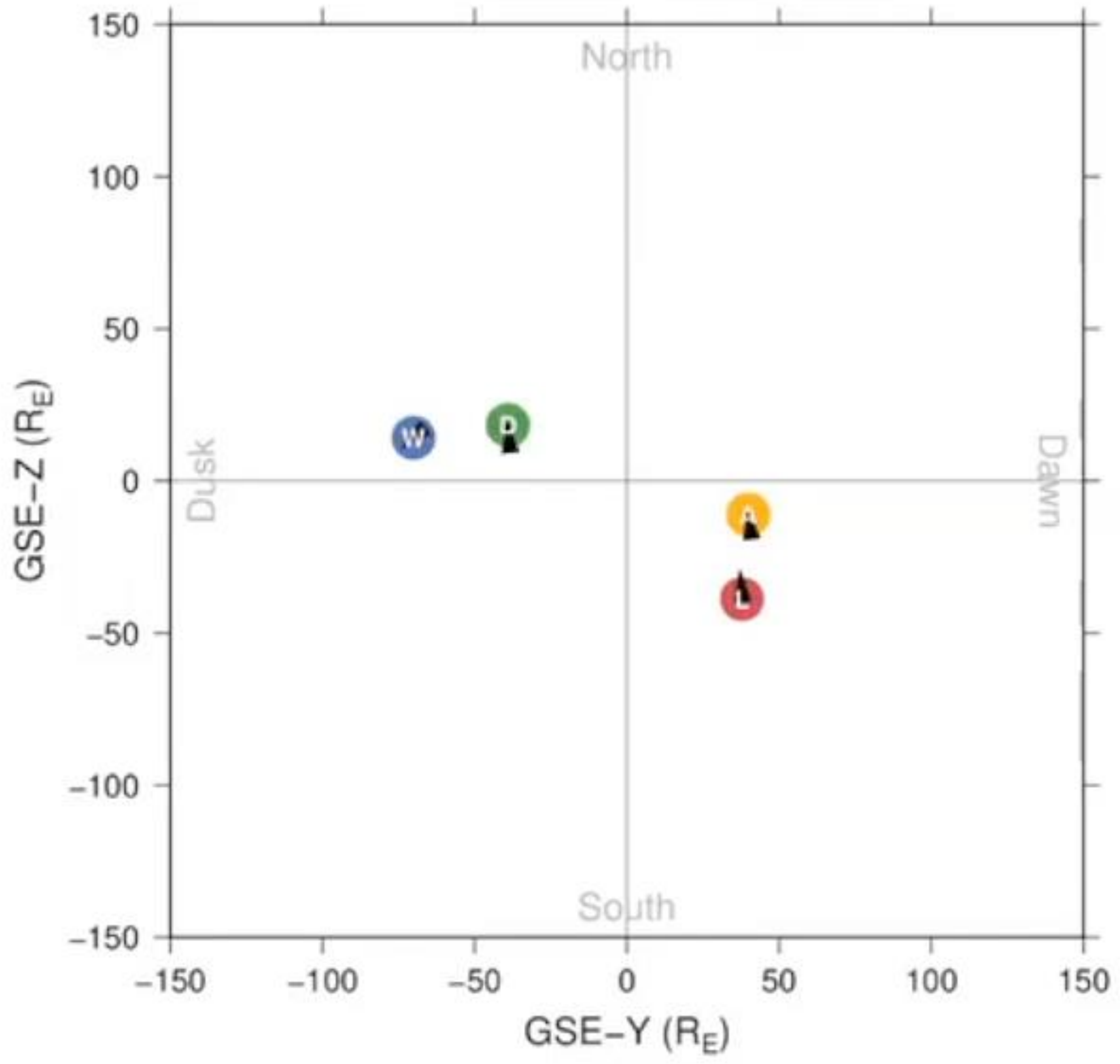


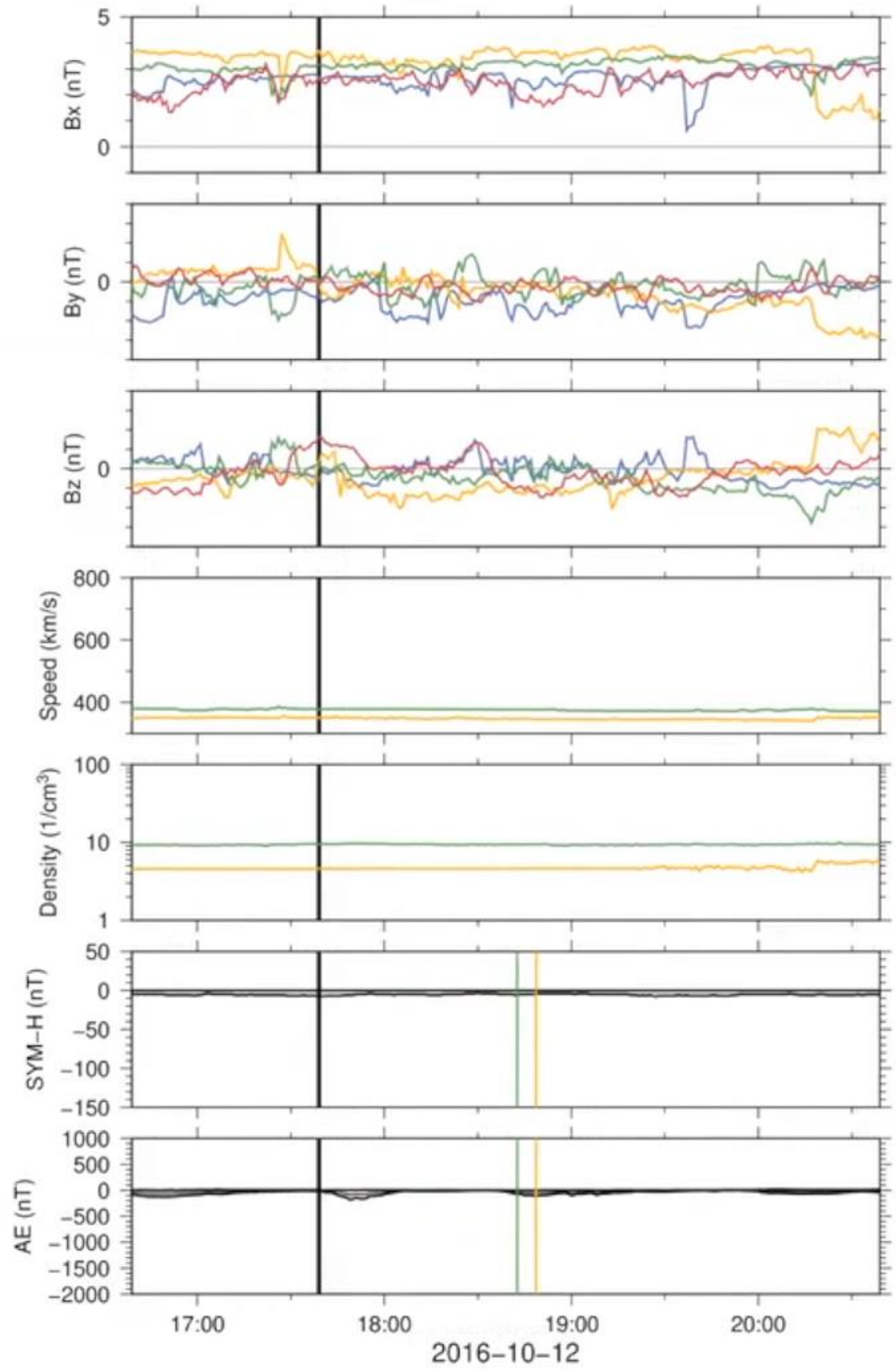
LISA pathfinder magnetometer perturbations induced by spacecraft subsystems (calibration curves based on ACE data)



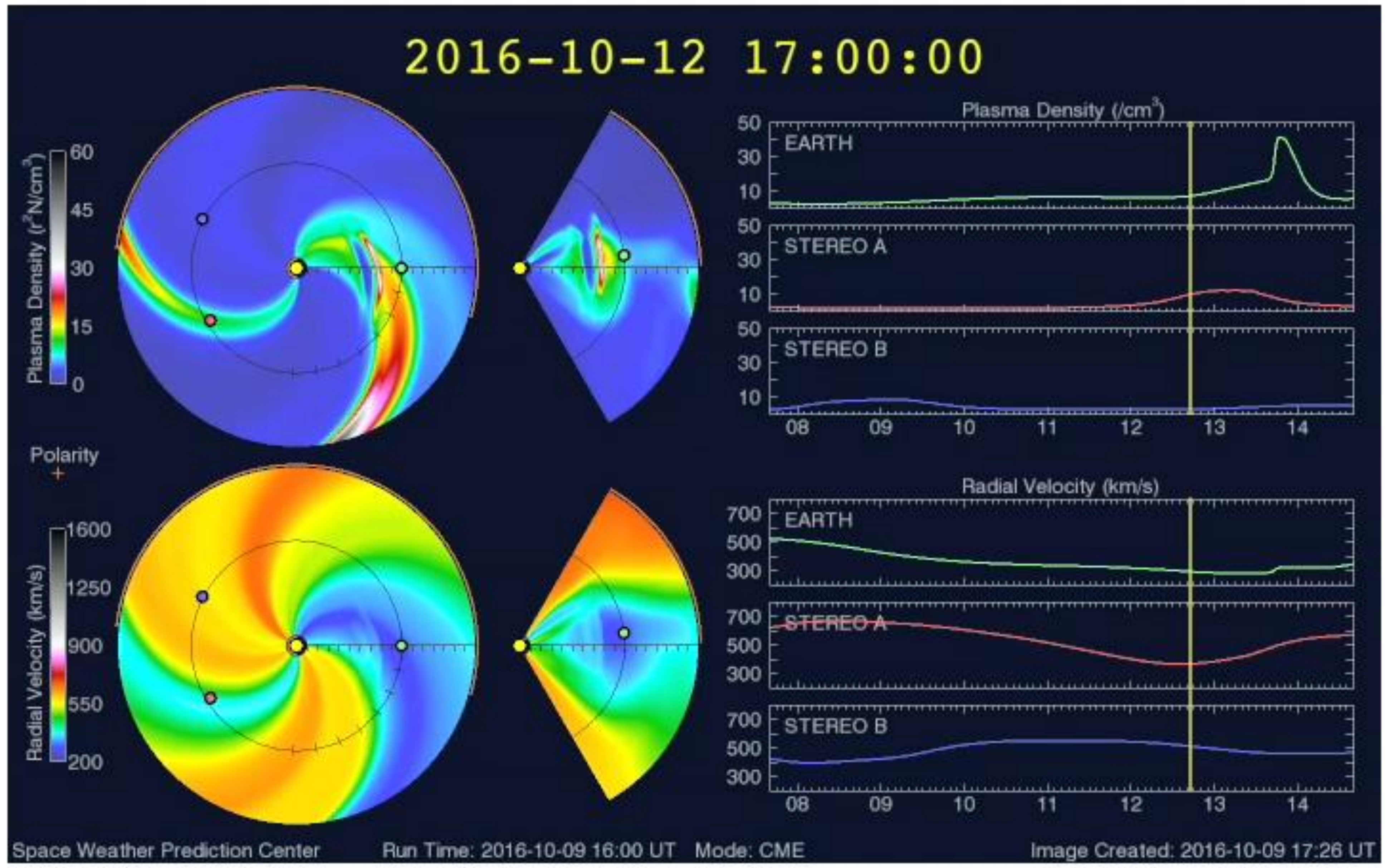
ACE data on IMF and solar wind
Ground magnetometers
Bx (nT)
By (nT)
Bz (nT)
Speed (km/s)
Density (1/cm^3)
SYM−H (nT)
AE (nT)
00:00
06:00
12:00
18:00
12 October 2016
13 October 2016
14 October 2016





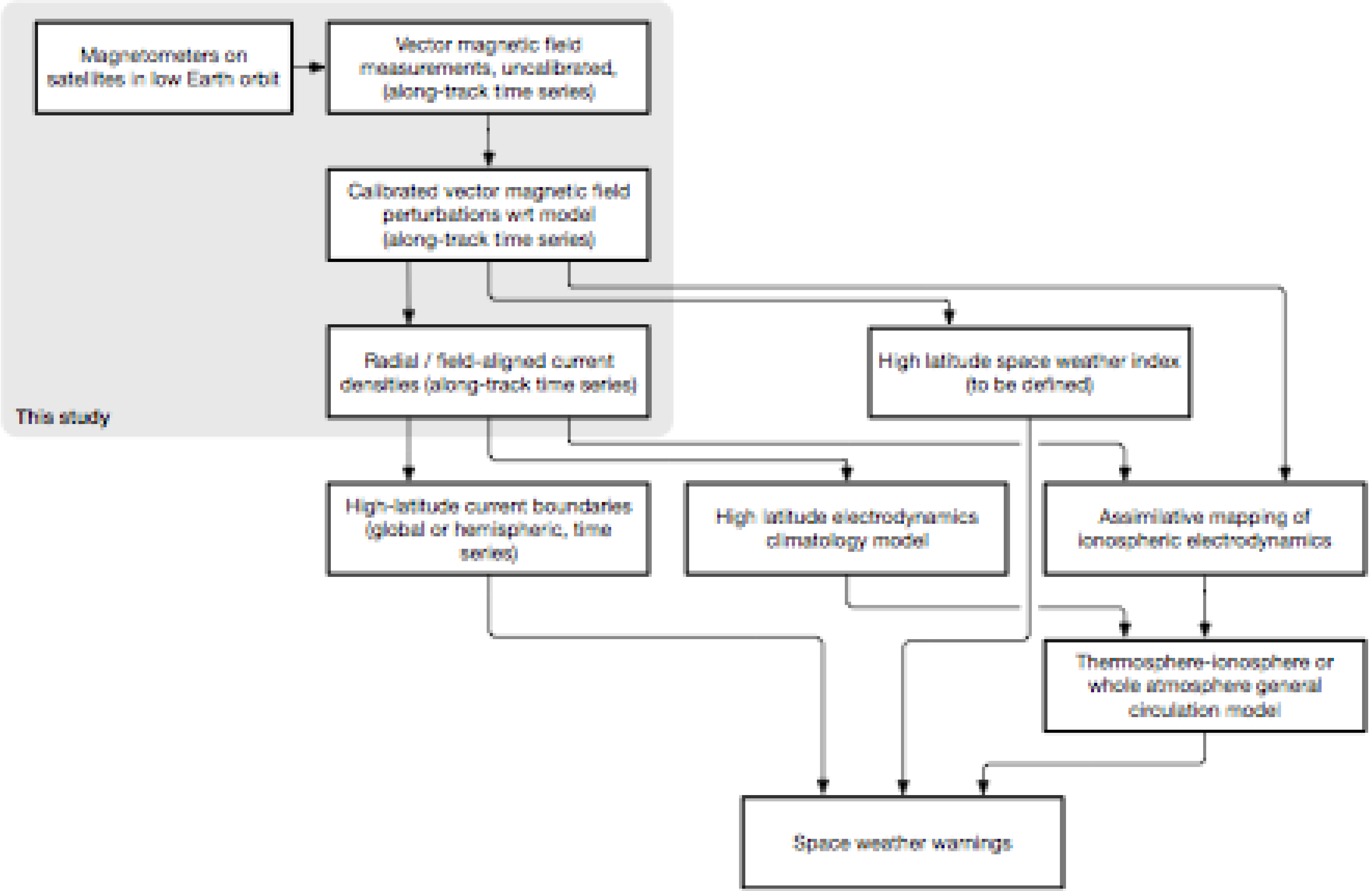


2016–10–12 17:39:00



Recommendations

Recommendation 2. Investigate space weather applications of higher-level products, using platform magnetometer and large scale field-aligned current data as inputs.

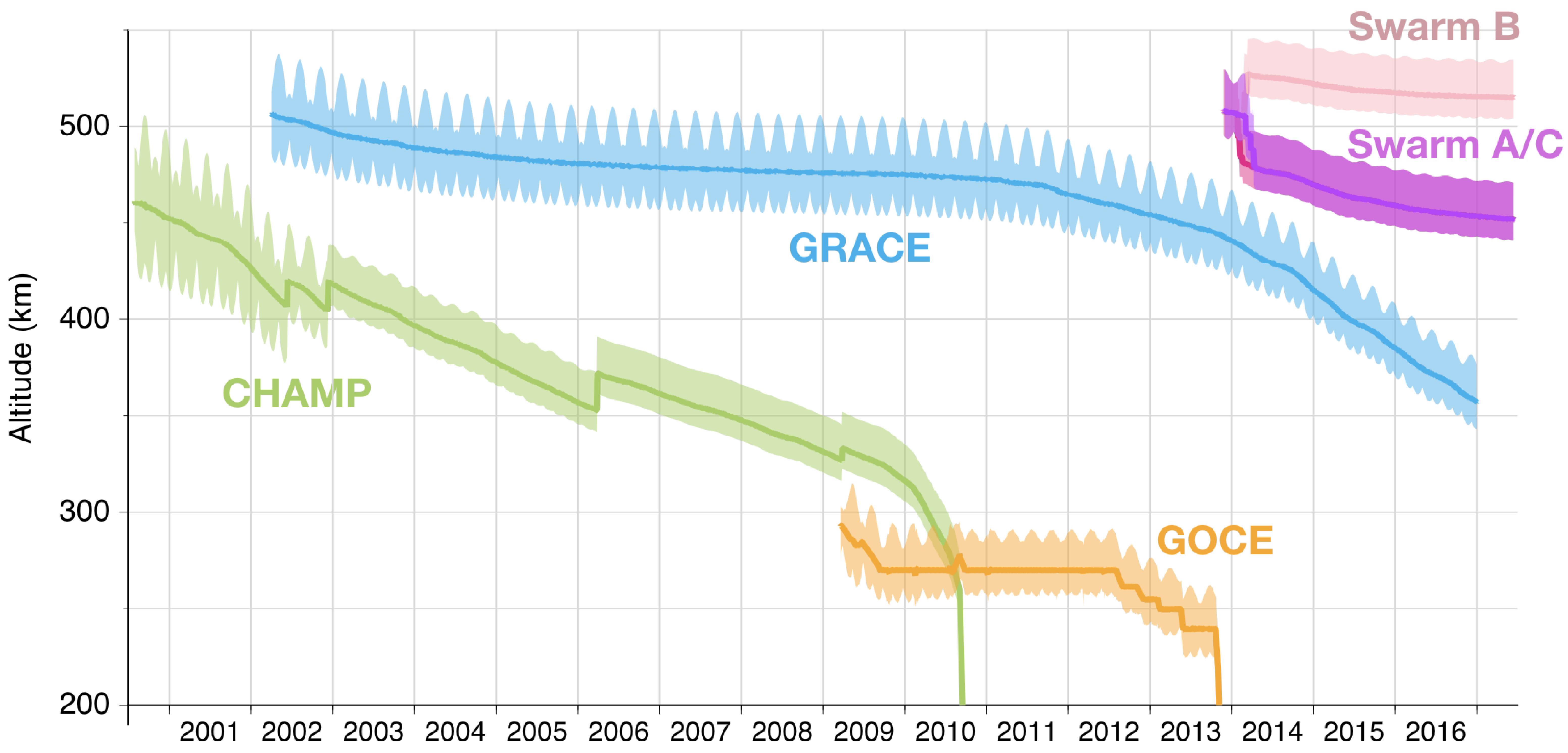


Candidate missions

Recommendation 6. Investigate missions with some or all of the characteristics listed below, as candidates for contributing platform magnetometer data for space weather applications.

- Missions with a high inclination orbit (near-polar, including sun-synchronous orbits), in order to cover the high-latitude current systems
- Satellite constellations (like the Iridium/AMPERE example).
- Missions with low latency data downlink capabilities, such as communications satellites, or those Earth observation missions which already have near real-time data product capabilities;
- Missions with a low number of moving parts on the spacecraft (for example gravity field missions, such as GOCE, GRACE and GRACE-FO, but also Cryosat-2);
- Long duration missions or mission sequences, such as GRACE and GRACE-FO, the Copernicus Sentinels.

Recommendation 9. Investigate the feasibility of using the magnetometer data of the GRACE and GRACE-FO missions, in an attempt to arrive at a multi-decade (2002-2017 and 2018-) magnetic field perturbation and field-aligned current dataset, that can accompany the GRACE thermosphere neutral density and wind datasets, and be used to improve the temporal and spatial sampling of existing datasets, such as from the AMPERE project.



Conclusions

- Platform magnetometers can provide excellent space weather information…
  - with some effort needed to set up the data processing, including stray field removal and calibration
  - to augment dedicated sensors and platforms, increasing spatial sampling
- The contribution of platform magnetometers to space weather monitoring can be significantly increased by initiating coordination and data processing activities, which are relatively low cost, compared to dedicated instruments/missions.
- The experience obtained during the project can be applied as well to future dedicated SSA/SWE missions, such as those studied under ESA’s D3S initiative.