Thermosphere data from acceleration measurements by **Swarm** and other satellites (mostly **GOCE**)

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TU Delft

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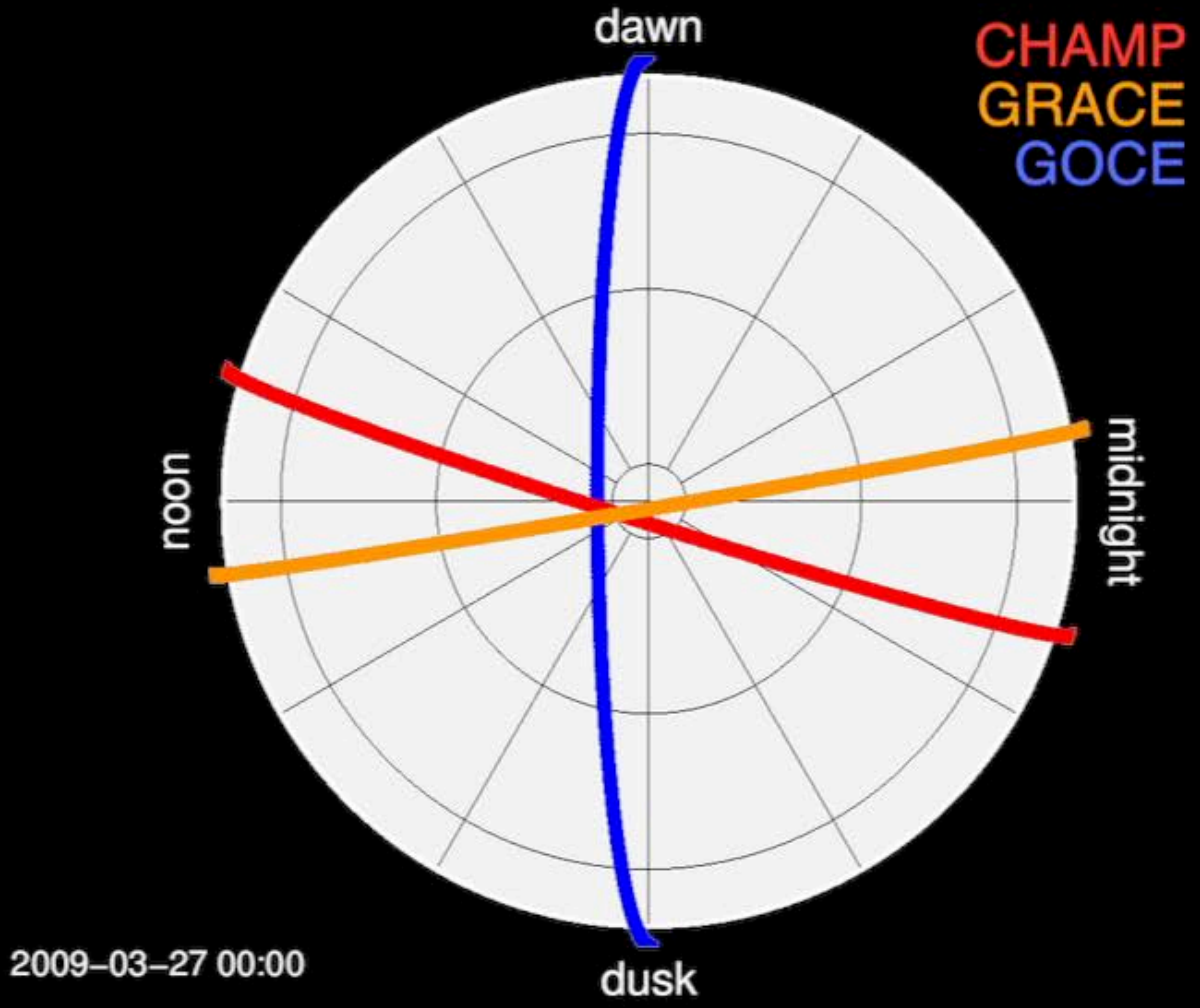
- Satellite missions and orbits
- Measurement principles and processing algorithms
- Swarm data overview, model comparisons and status
- GOCE data / model comparisons
- Future plans

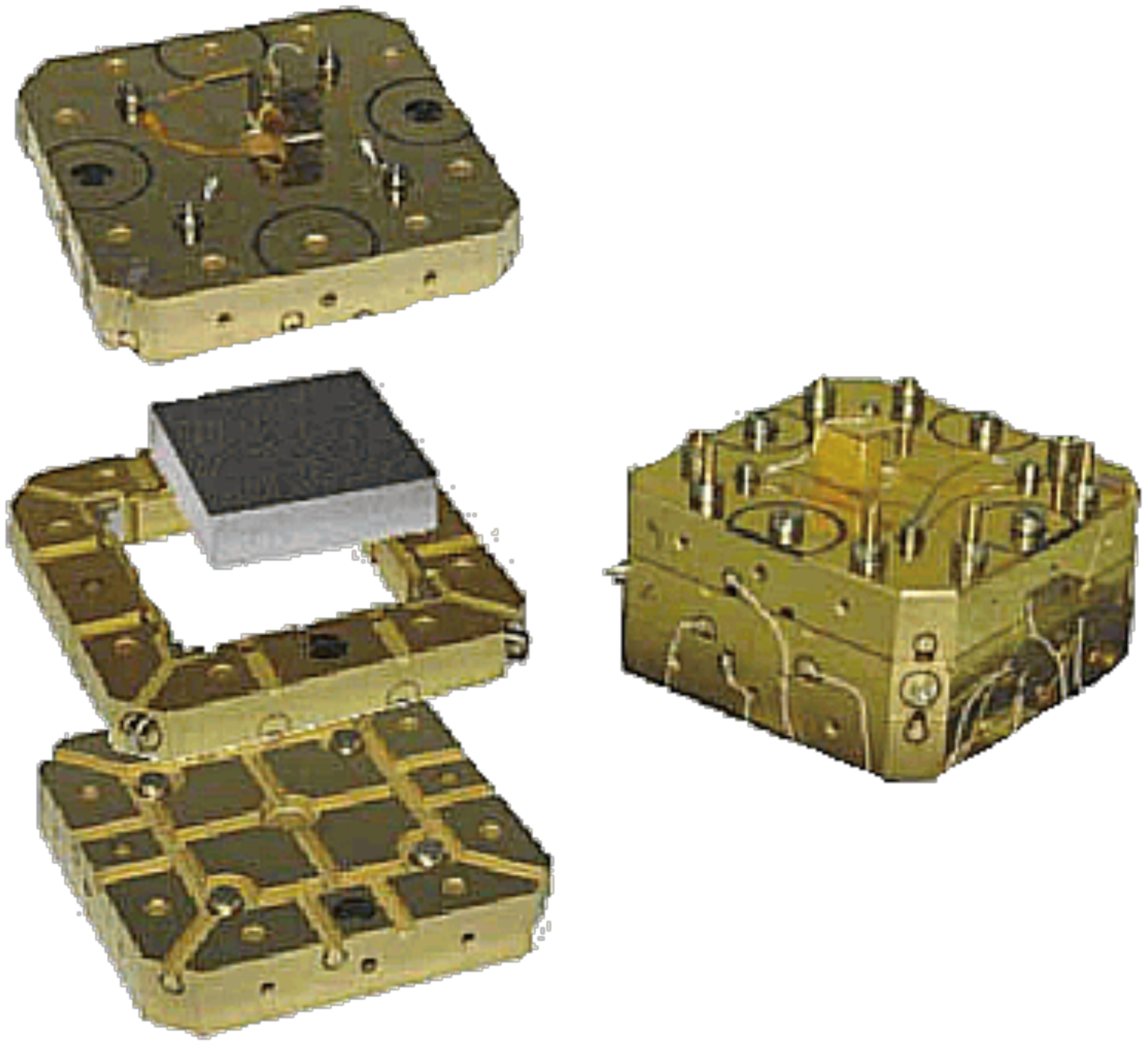
Accelerometer satellites

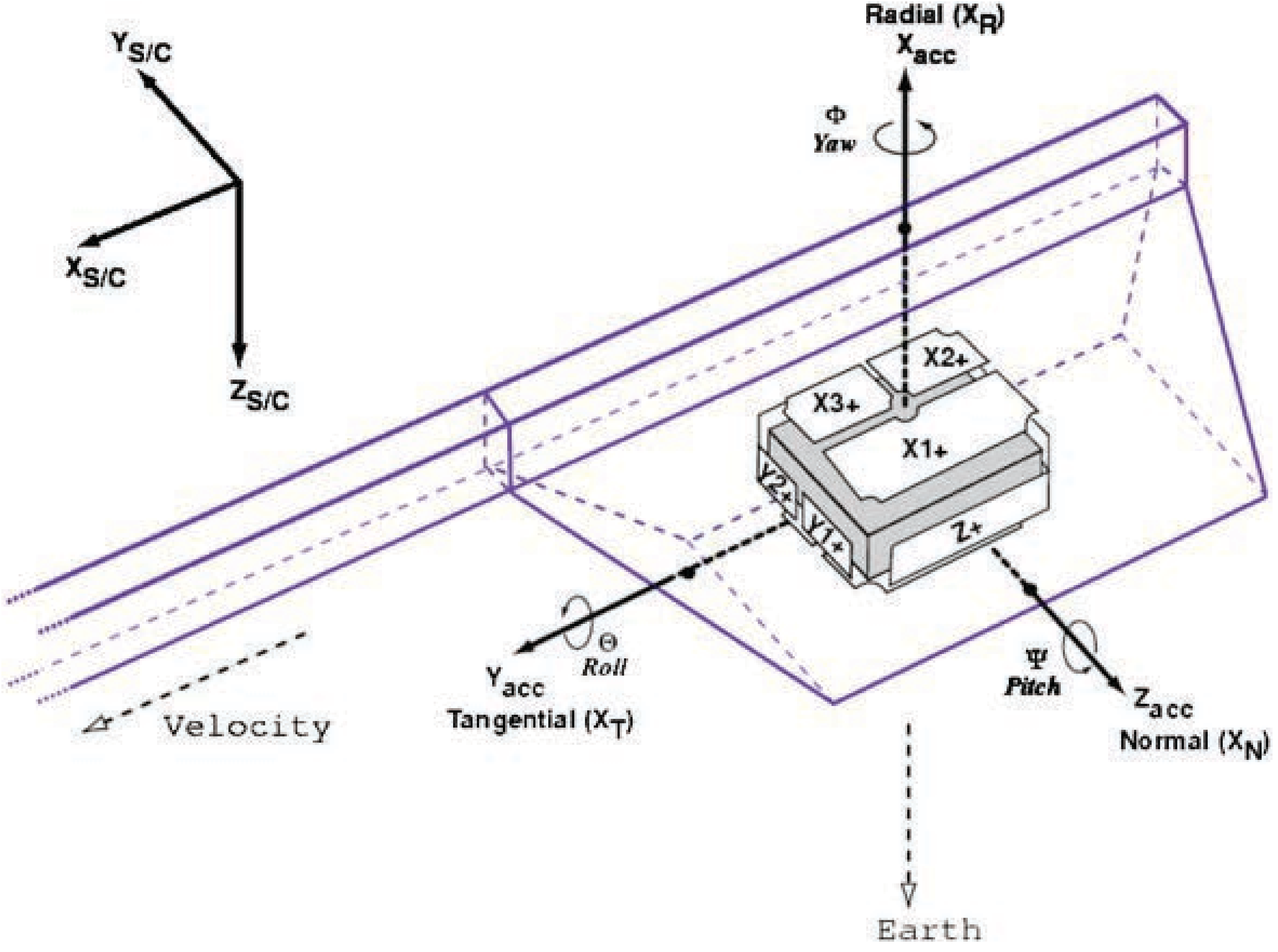
Accelerometer satellites

Orbit planes of CHAMP, GRACE and GOCE
view of the Northern Hemisphere



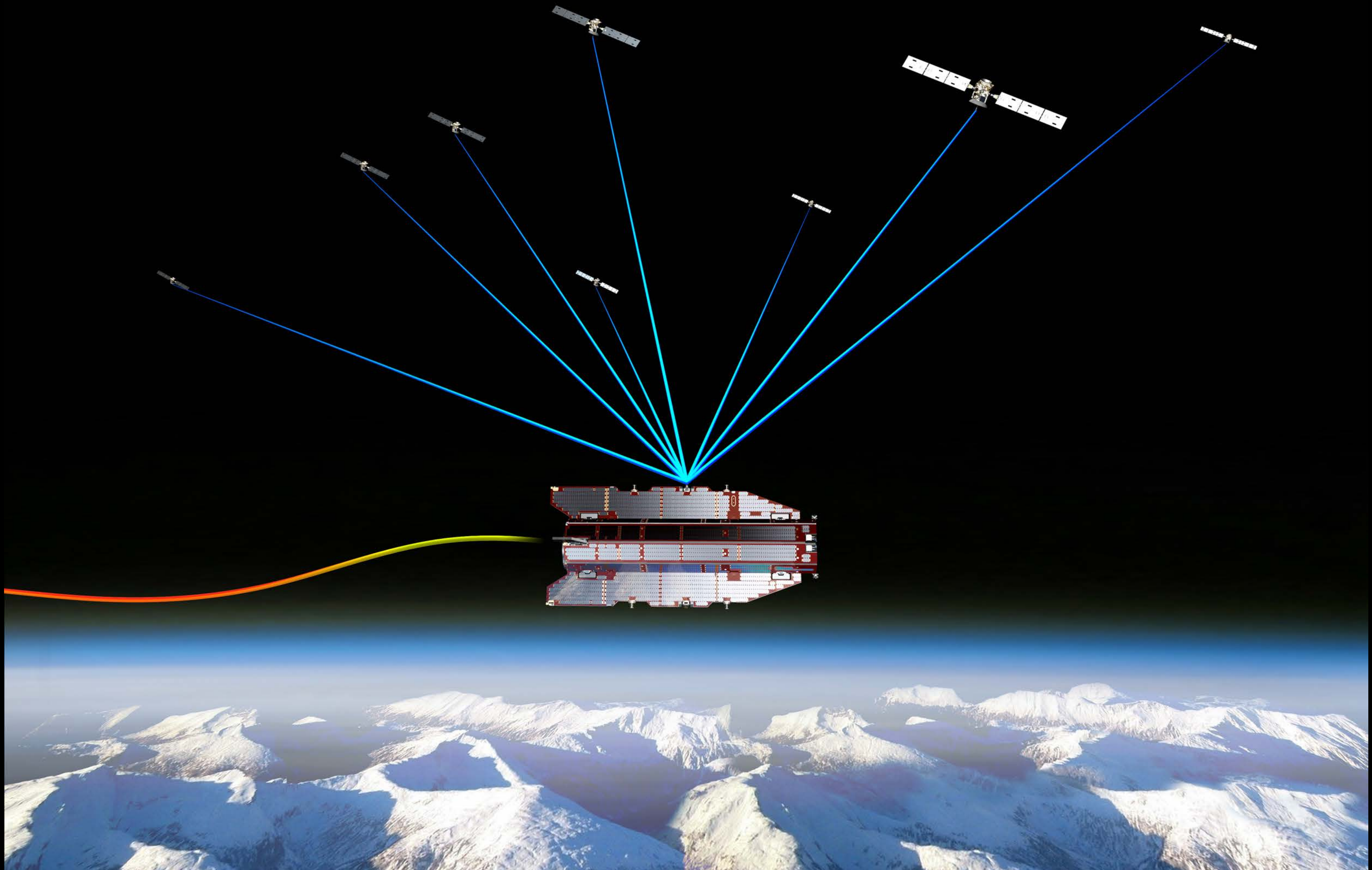
Accelerometer measurement principle





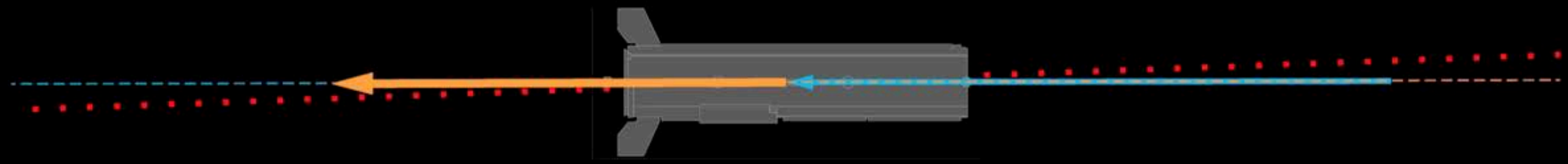
Figures: GFZ-Potsdam / CNES / ONERA

GPS acceleration measurement principle



Isolating aerodynamic accelerations

From aerodynamic accelerations to density and wind

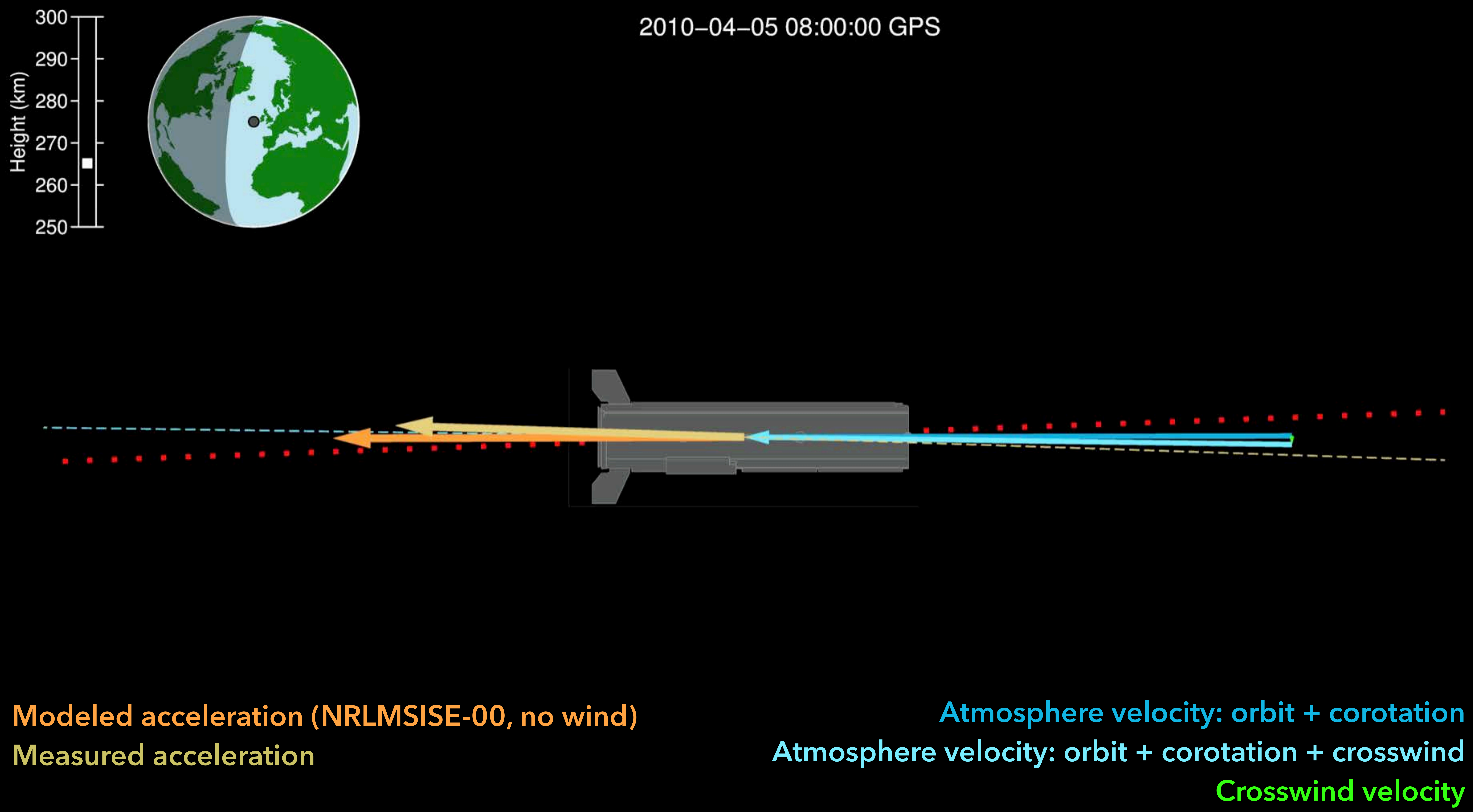


Relative velocity of atmosphere

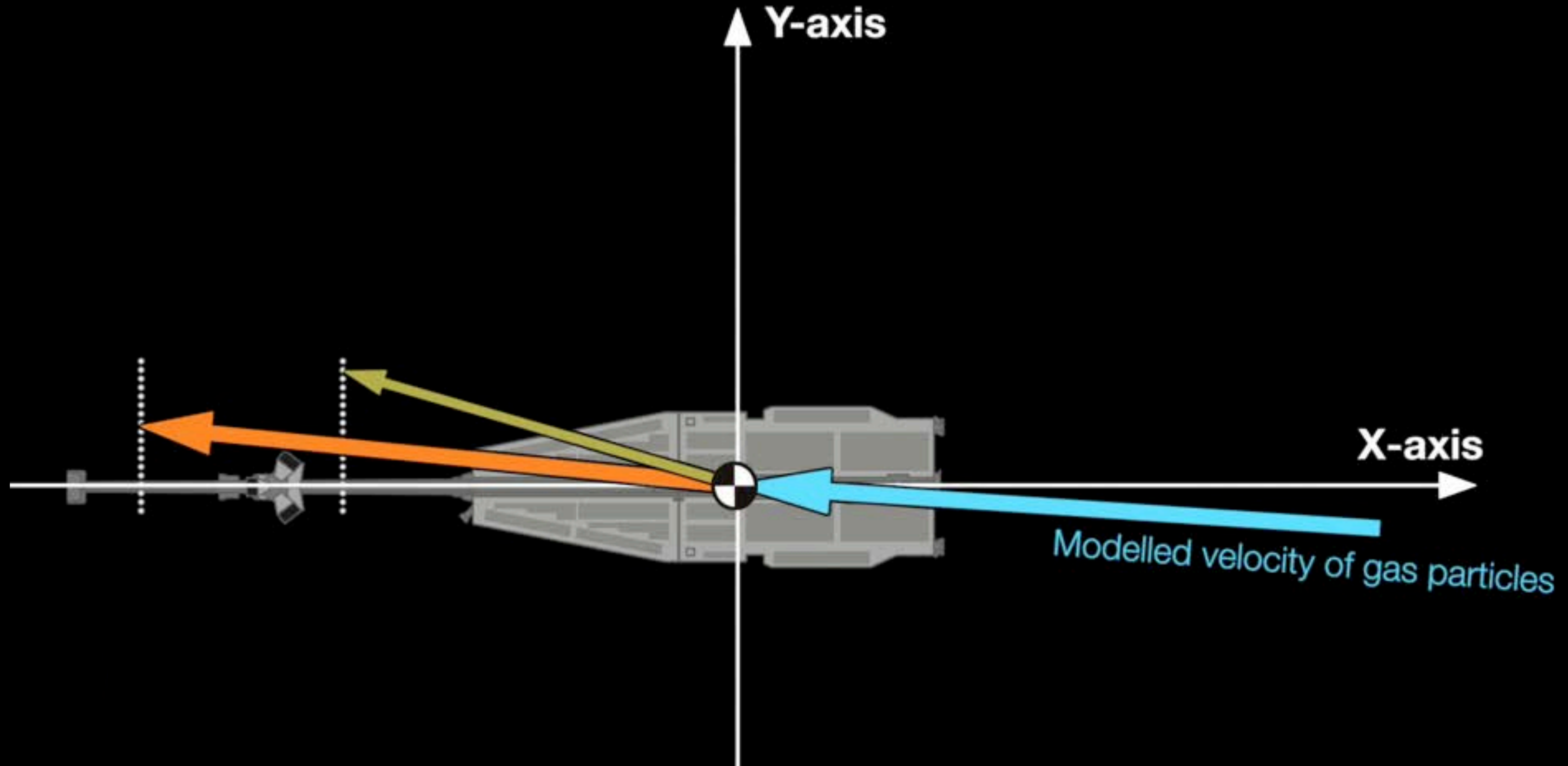
Satellite aerodynamic model:
- Geometry
- Gas-surface interaction

Density model (e.g. NRLMSISE-00)

Modeled acceleration


2010–04–05 08:00:00 GPS
Height (km)
300
290
280
270
260
250
Modeled acceleration (NRLMSISE-00, no wind)
Measured acceleration
Atmosphere velocity: orbit + corotation
Atmosphere velocity: orbit + corotation + crosswind
Crosswind velocity

If Y-axis data is inaccurate, wind determination is not possible. We then use only the good X-axis data to determine density.



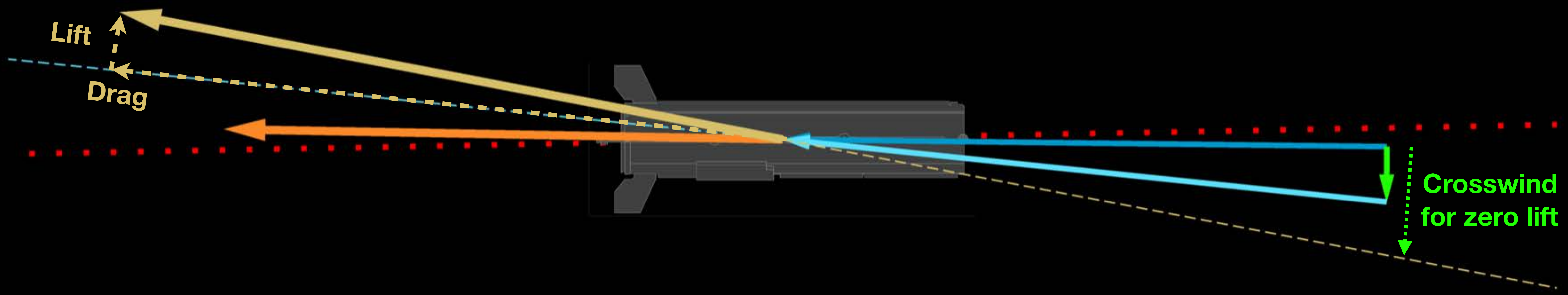
Caveats

- Obtaining thermosphere data is (at best) a secondary objective for these missions.
- Wind determination is only possible at very high densities.
- Densities below about 10^{-13} kg/m^3 are severely affected by radiation pressure model error. Need to use orbit-average data.
- Swarm accelerometers suffer from severe problems: temperature sensitivity, frequent bias jumps, spurious signals. Only Swarm C is good enough to perform correction of the data.
- CHAMP and GRACE started to suffer from poor batteries after ~8 years in orbit. Remedies (heater switch-off and periodic ACC instrument switch-off on GRACE) have affected the accelerometer data.

	CHAMP	GRACE	GOCE	Swarm C (ACC+GPS)	Swarm A, B, C (GPS only)	GRACE-FO
Years of data	2001-2010	2002-now processed until 2008	2009-2013	June 2014-?	Dec 2013-?	2018-?
Instruments	ACC+GPS	ACC+GPS	EGG+GPS	ACC+GPS	GPS	ACC+GPS
Data rate	10 sec	10 sec	10 sec	~10 sec	30 sec, ~20 min smoothing	5 sec or better
Density data quality	Excellent before 2008	Very good until ~2007	Excellent	Variable between poor and good	Very good at medium-high solar activity	TBD
Wind data quality	Good from 2001-2004	Poor	Excellent	Not available	Not available	TBD

Status mid 2017 for data processed at TU Delft. More GRACE data might be available from Sean Bruinsma or Eric Sutton.
For questions on use of data, email e.n.doornbos@tudelft.nl

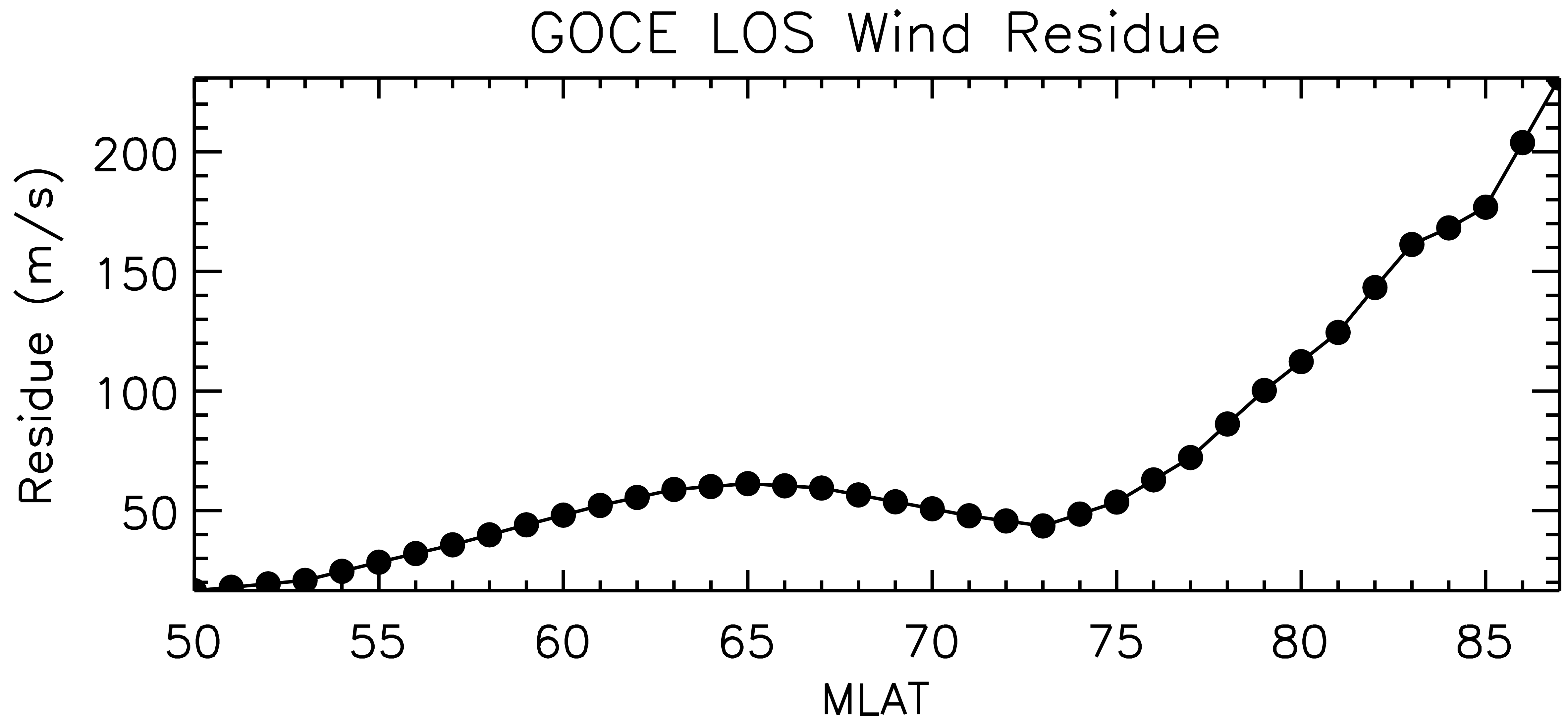
Drag, lift and crosswind



Crosswind competes with aerodynamic lift in explaining cross-track acceleration.

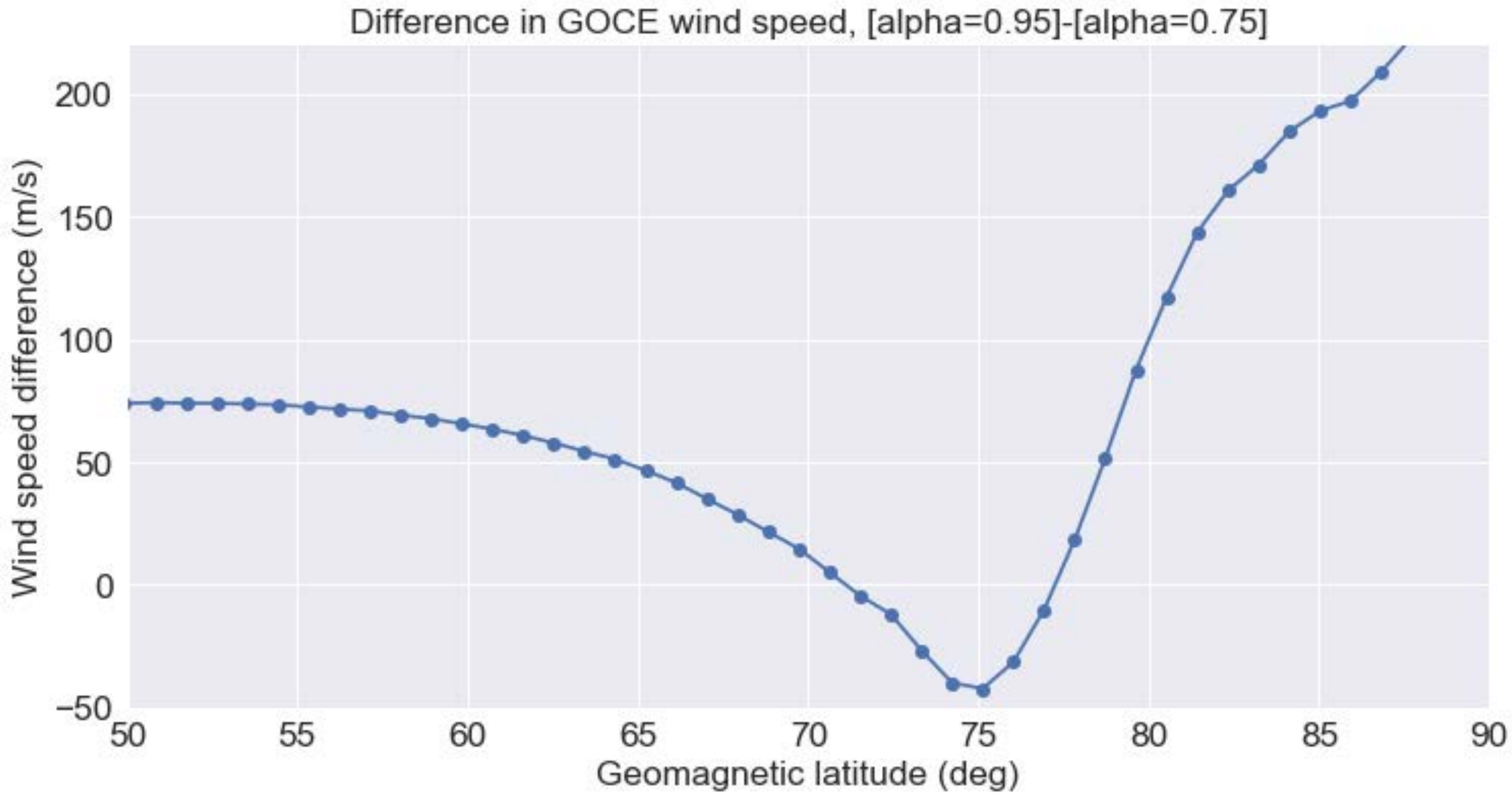
The aerodynamic lift is dependent on:

- Incidence angle (dependent on satellite attitude and wind)
- Gas-surface interaction parameters (energy accommodation, mode of reflection)



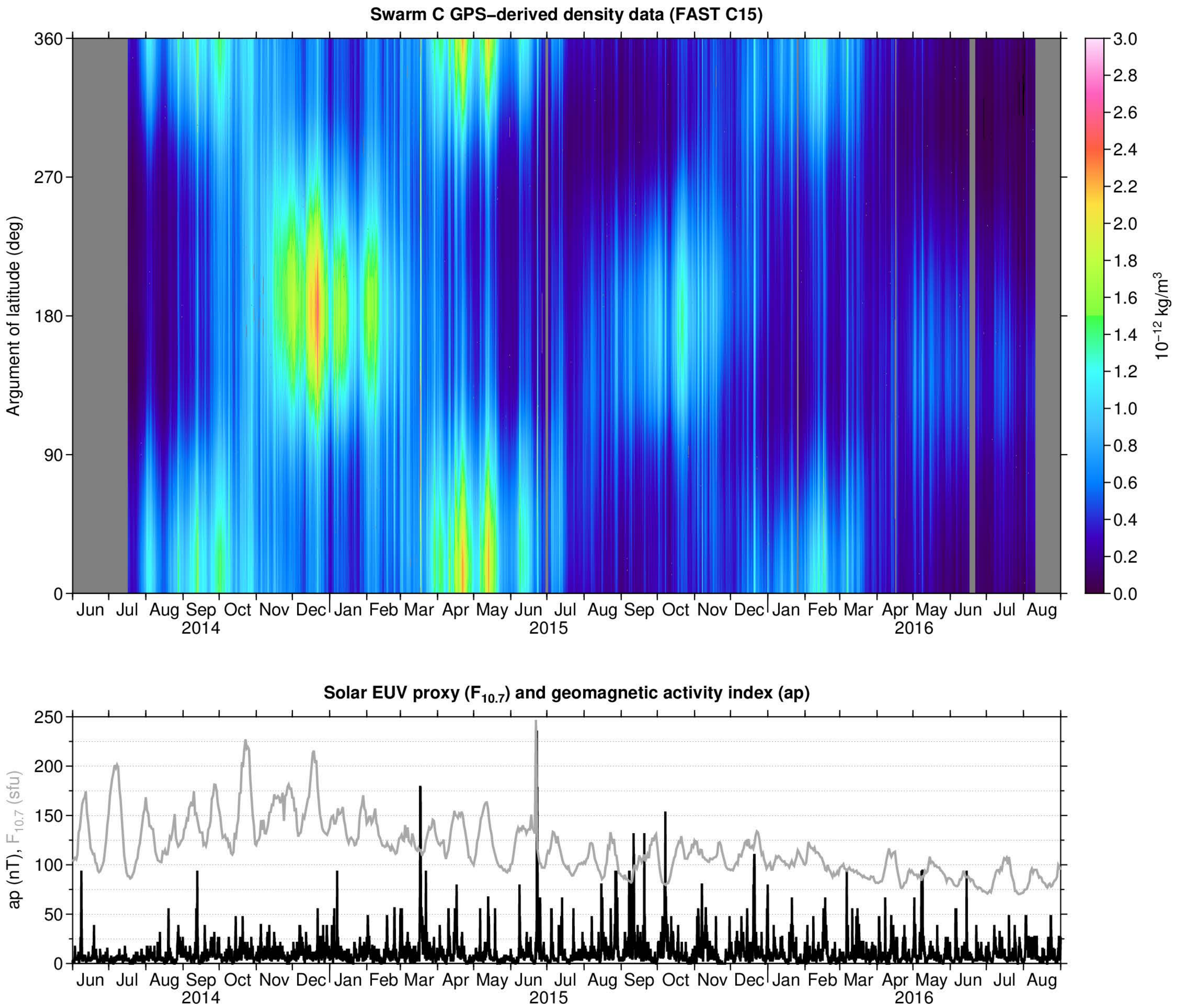
Left: Figure from Monday's presentation in Polar Workshop, by Manbharat Dhadly (NRL), showing average discrepancy between GOCE wind and all other wind data in MLAT bins.

Below: Average differences in MLAT bins of GOCE datasets processed with two different settings of the energy accommodation coefficient, resulting in different levels of lift.

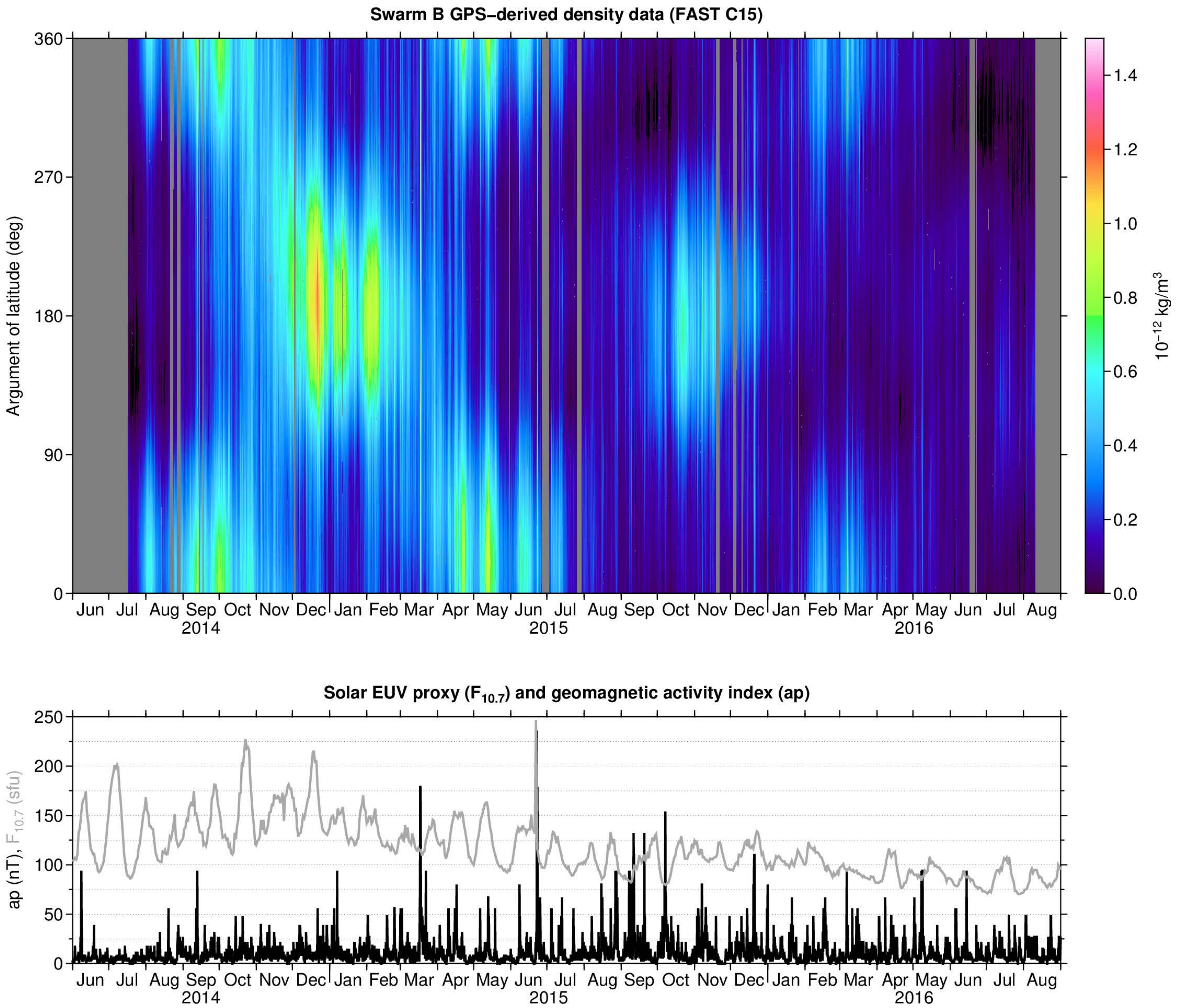


Swarm data overview

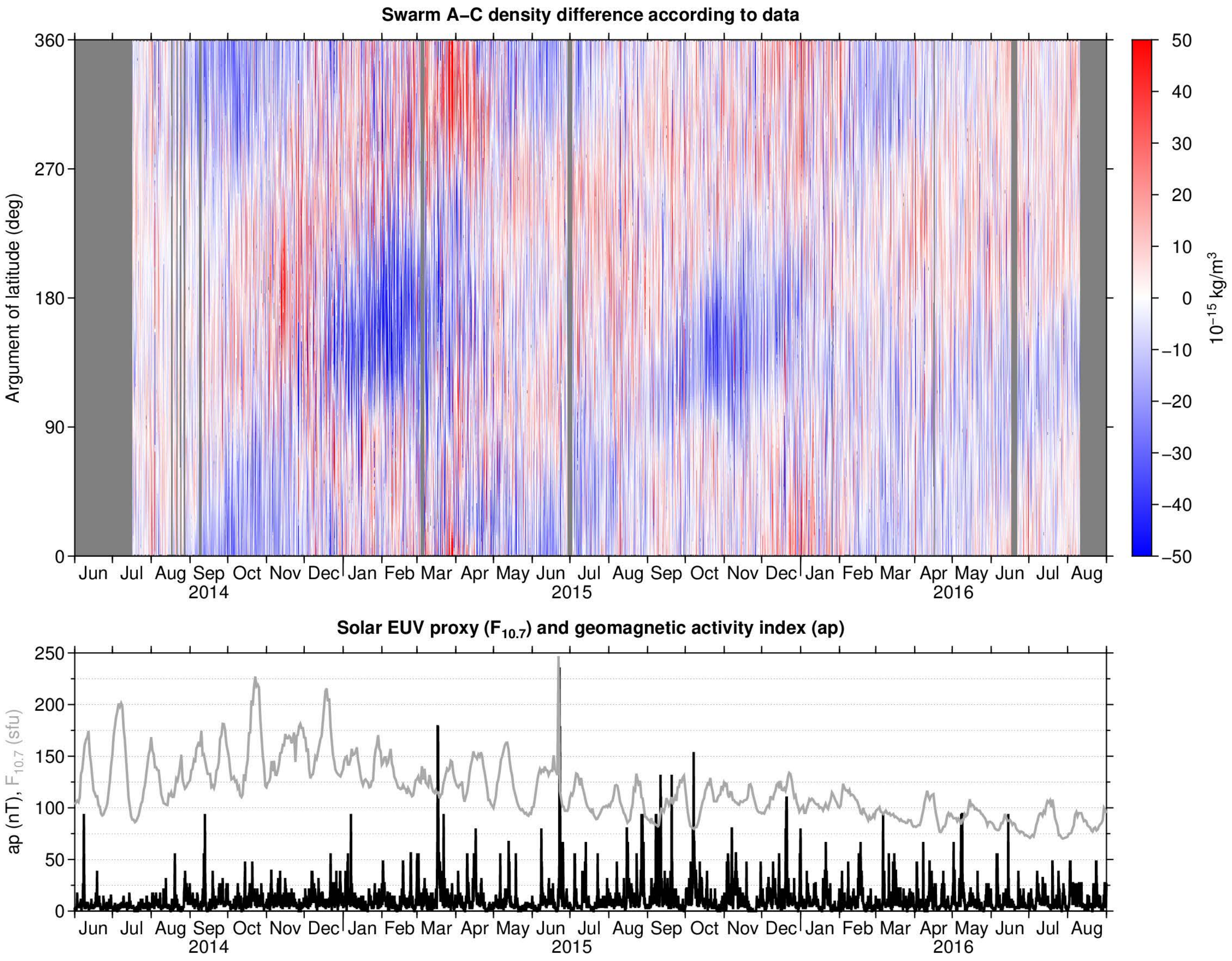
- Accelerometer-derived thermosphere density data (DNSCWND) only available for Swarm C. Routine processing not yet started.
- GPS-only thermosphere density product (DNSxPOD) is now available for all three satellites, for 2014-2016. Routine data processing with a few weeks latency is starting this month.
    - Product has much lower temporal resolution than accelerometer data (20 minutes instead of 10 seconds).
    - Product also includes orbit-average density for use at low solar activity.



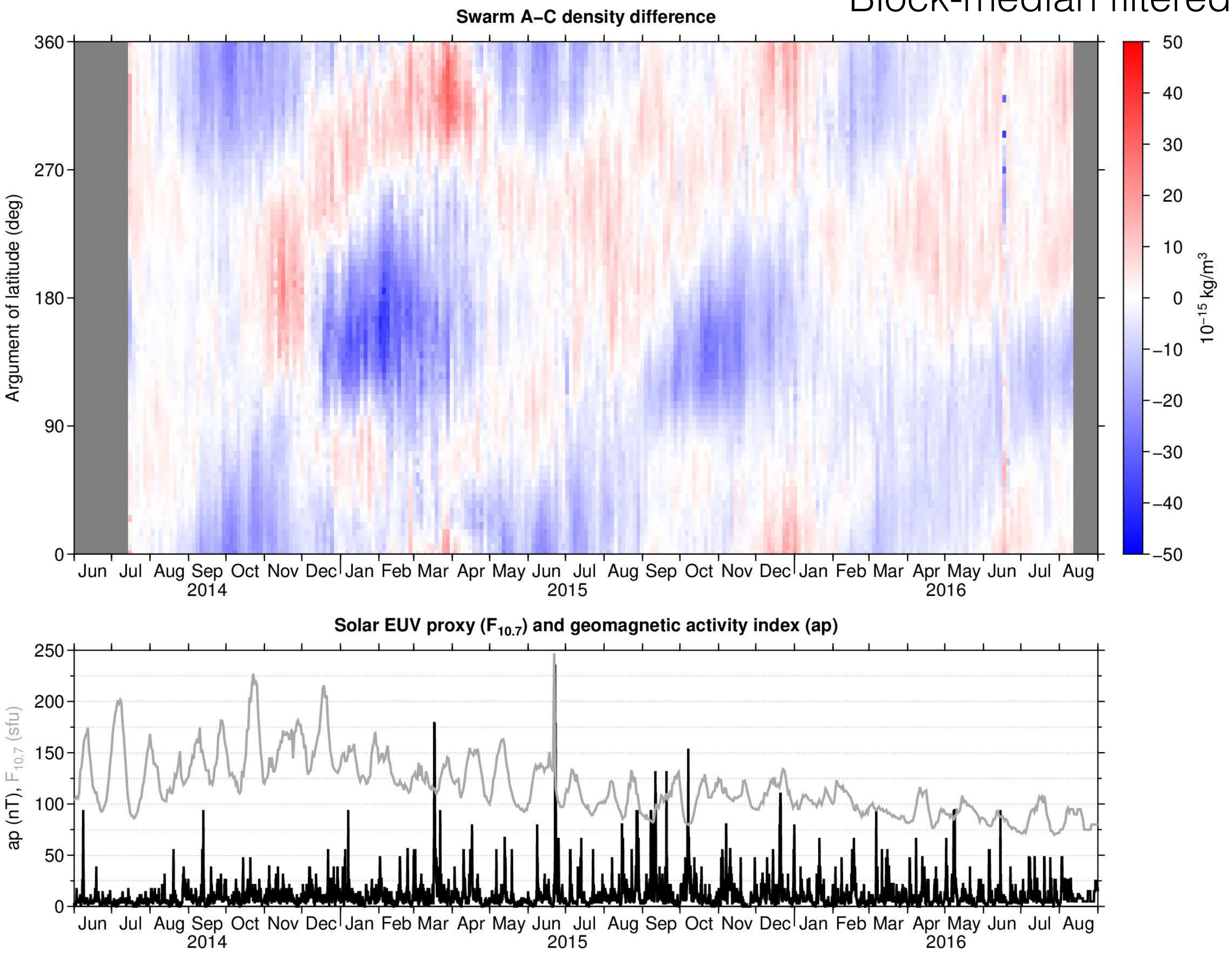
Swarm C GPS-derived density data (FAST C15)
Argument of latitude (deg)
360
270
180
90
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016
10^{-12} kg/m^3
3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
Solar EUV proxy ($F_{10.7}$) and geomagnetic activity index (ap)
ap (nT), $F_{10.7}$ (sfu)
250
200
150
100
50
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016

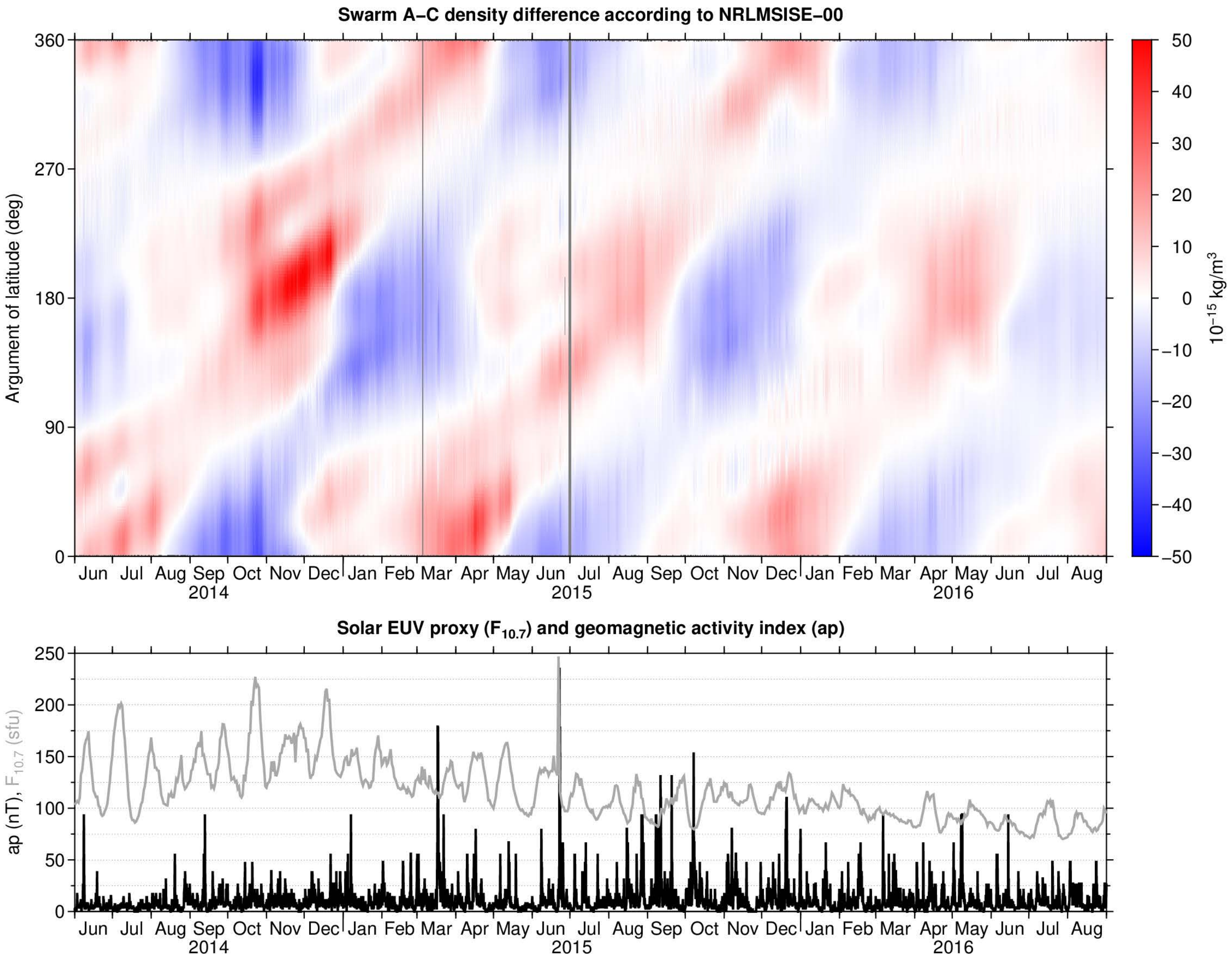


Swarm B GPS−derived density data (FAST C15)
Argument of latitude (deg)
0
90
180
270
360
10−12 kg/m3
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016
Solar EUV proxy (F10.7) and geomagnetic activity index (ap)
ap (nT), F10.7 (sfu)
0
50
100
150
200
250
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016

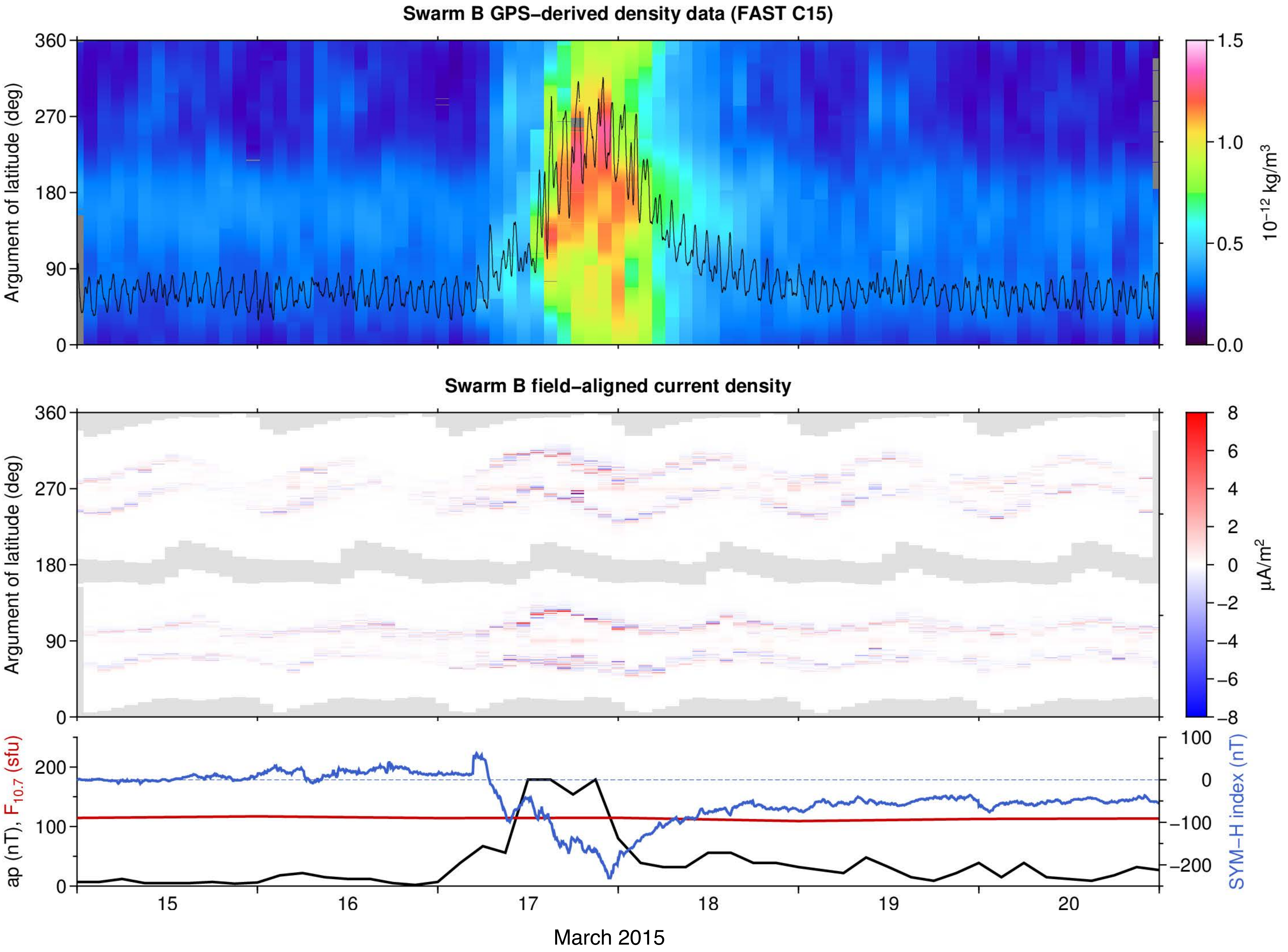

Swarm A−C density difference according to data
Argument of latitude (deg)
360
270
180
90
0
50
40
30
20
10
0
−10
−20
−30
−40
−50
10^{-15} kg/m^3
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016
Solar EUV proxy ($F_{10.7}$) and geomagnetic activity index (ap)
ap (nT), $F_{10.7}$ (sfu)
250
200
150
100
50
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016

Block-median filtered

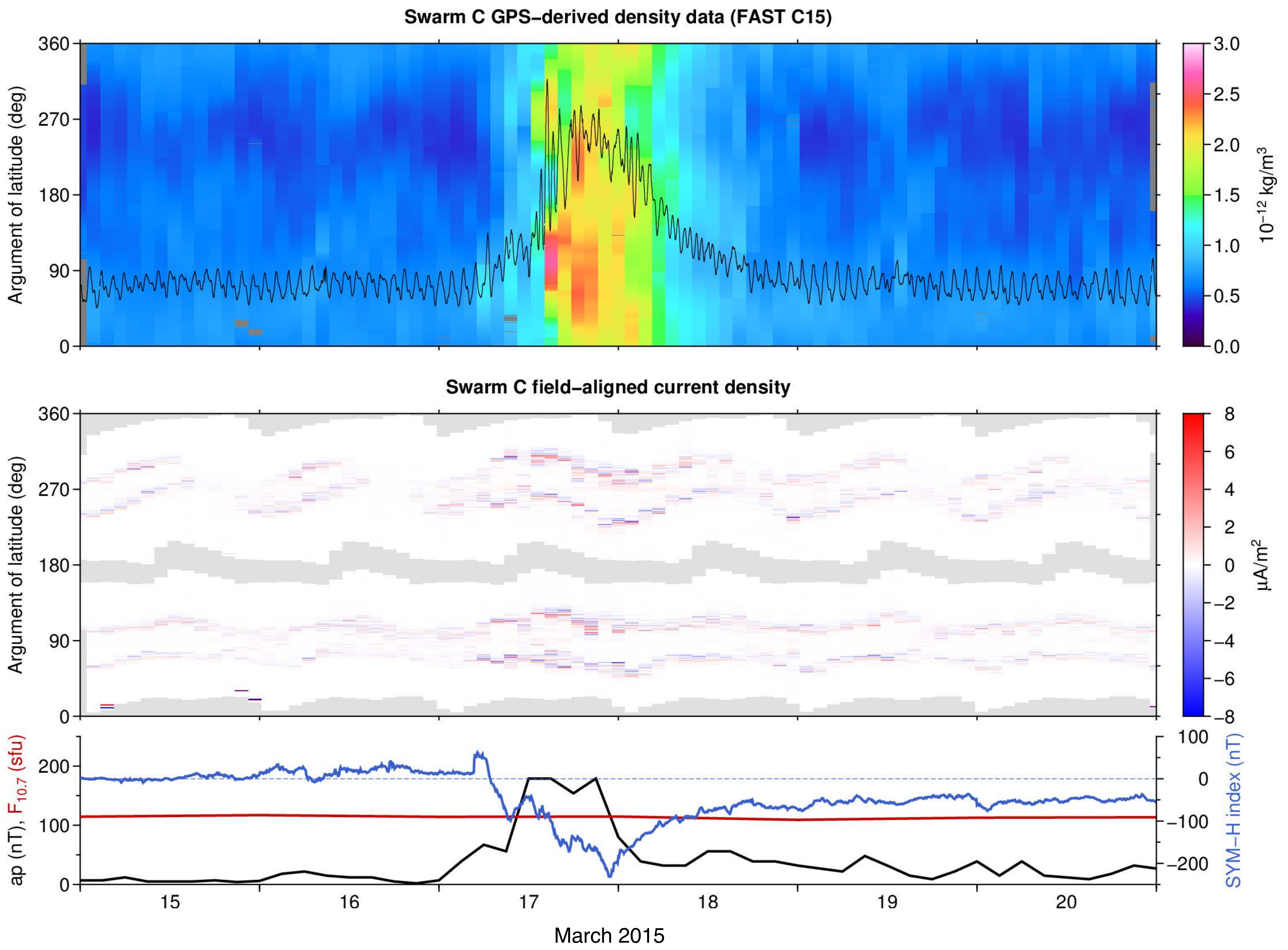




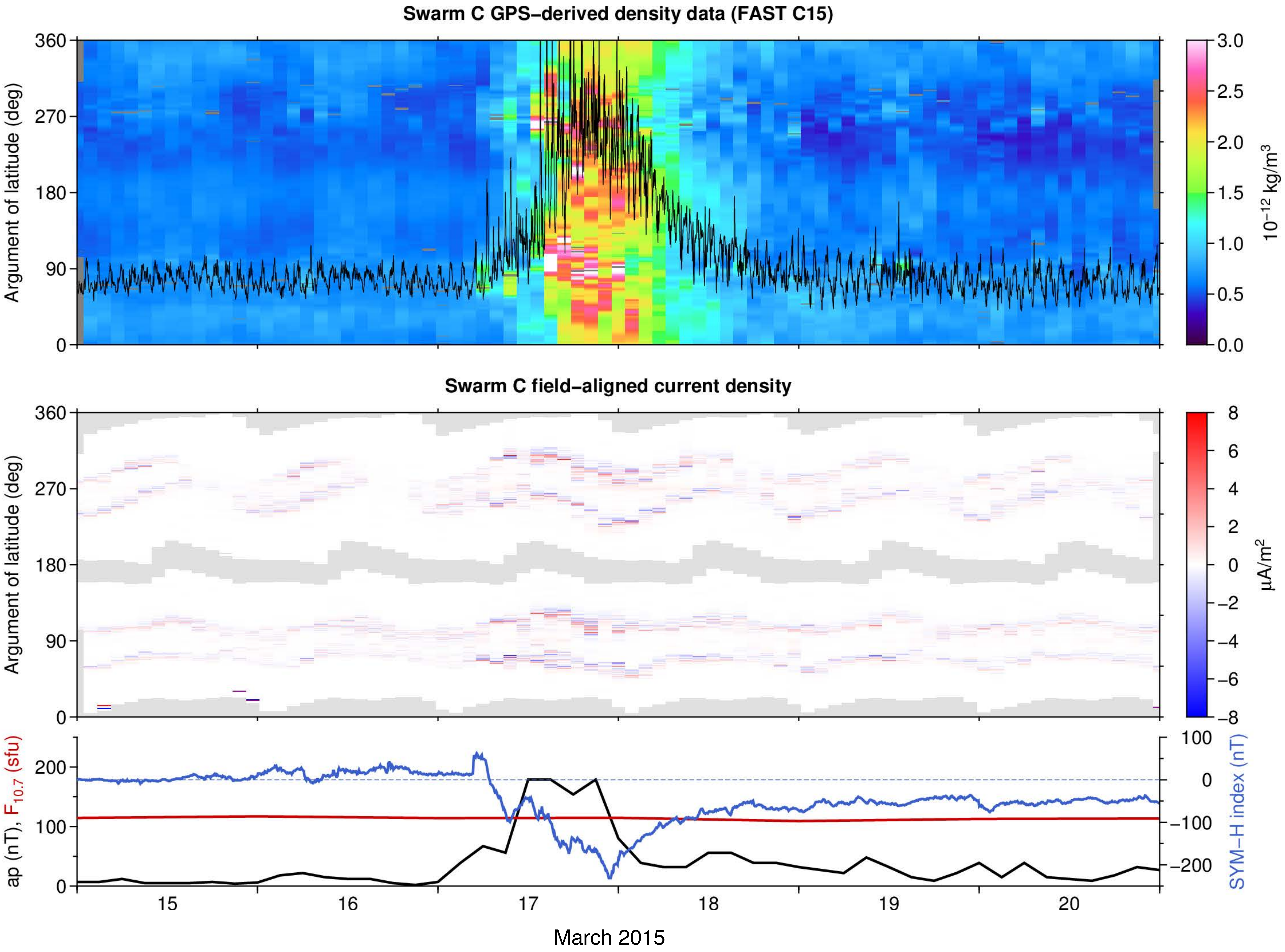
Swarm A−C density difference according to NRLMSISE−00
Argument of latitude (deg)
360
270
180
90
0
10⁻¹⁵ kg/m³
50
40
30
20
10
0
−10
−20
−30
−40
−50
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016
Solar EUV proxy (F10.7) and geomagnetic activity index (ap)
ap (nT), F10.7 (sfu)
250
200
150
100
50
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
2014
2015
2016



Swarm B GPS-derived density data (FAST C15)
Argument of latitude (deg)
10⁻¹² kg/m³
Swarm B field-aligned current density
Argument of latitude (deg)
μA/m²
ap (nT), F10.7 (sfu)
SYM-H index (nT)
March 2015

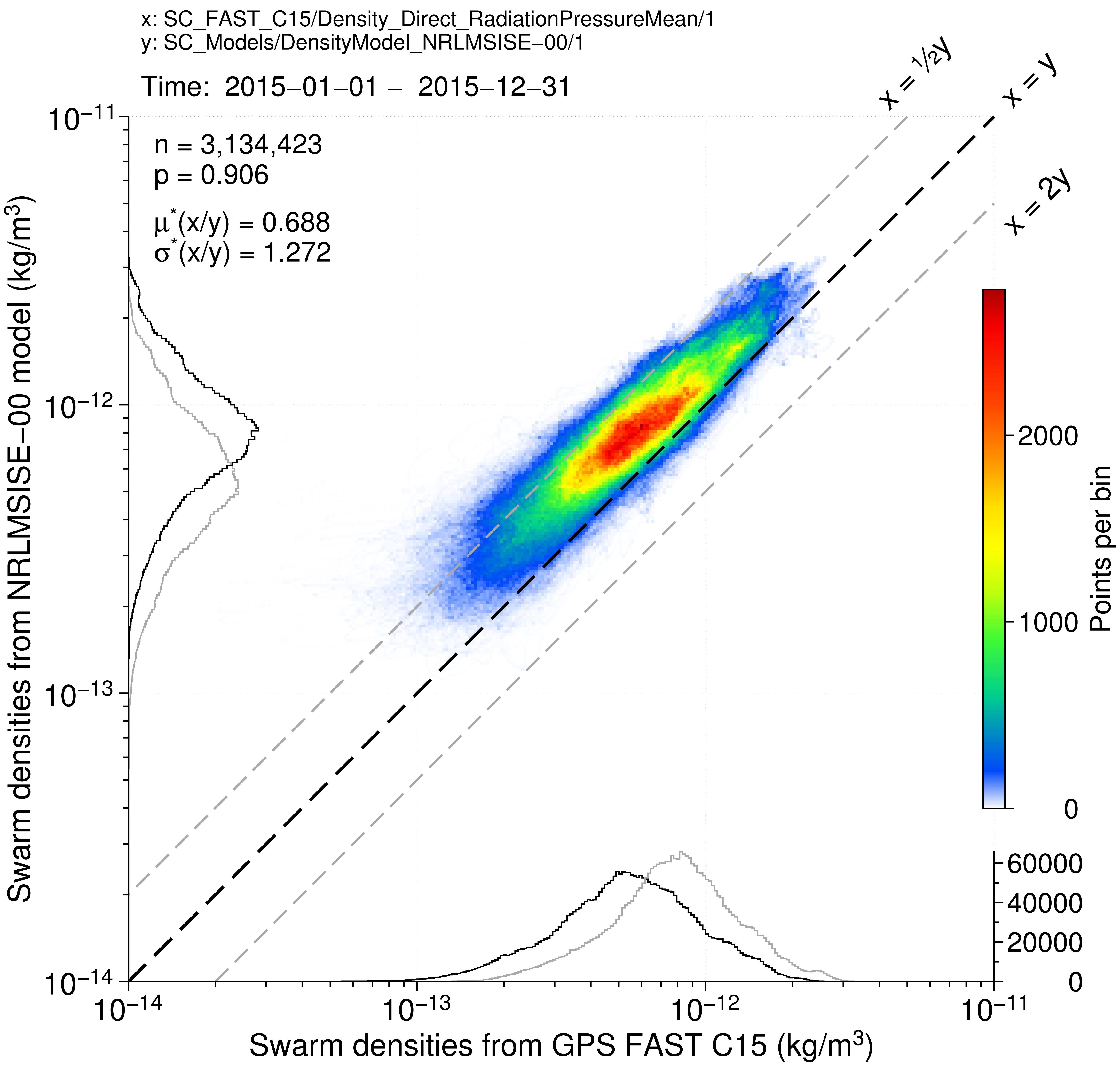


Swarm C GPS-derived density data (FAST C15)
Argument of latitude (deg)
360
270
180
90
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^{-12} kg/m^3
Swarm C field-aligned current density
Argument of latitude (deg)
8
6
4
2
0
−2
−4
−6
−8
μA/m^2
ap (nT), $F_{10.7}$ (sfu)
SYM−H index (nT)
200
100
0
100
0
−100
−200
15
16
17
18
19
20
March 2015

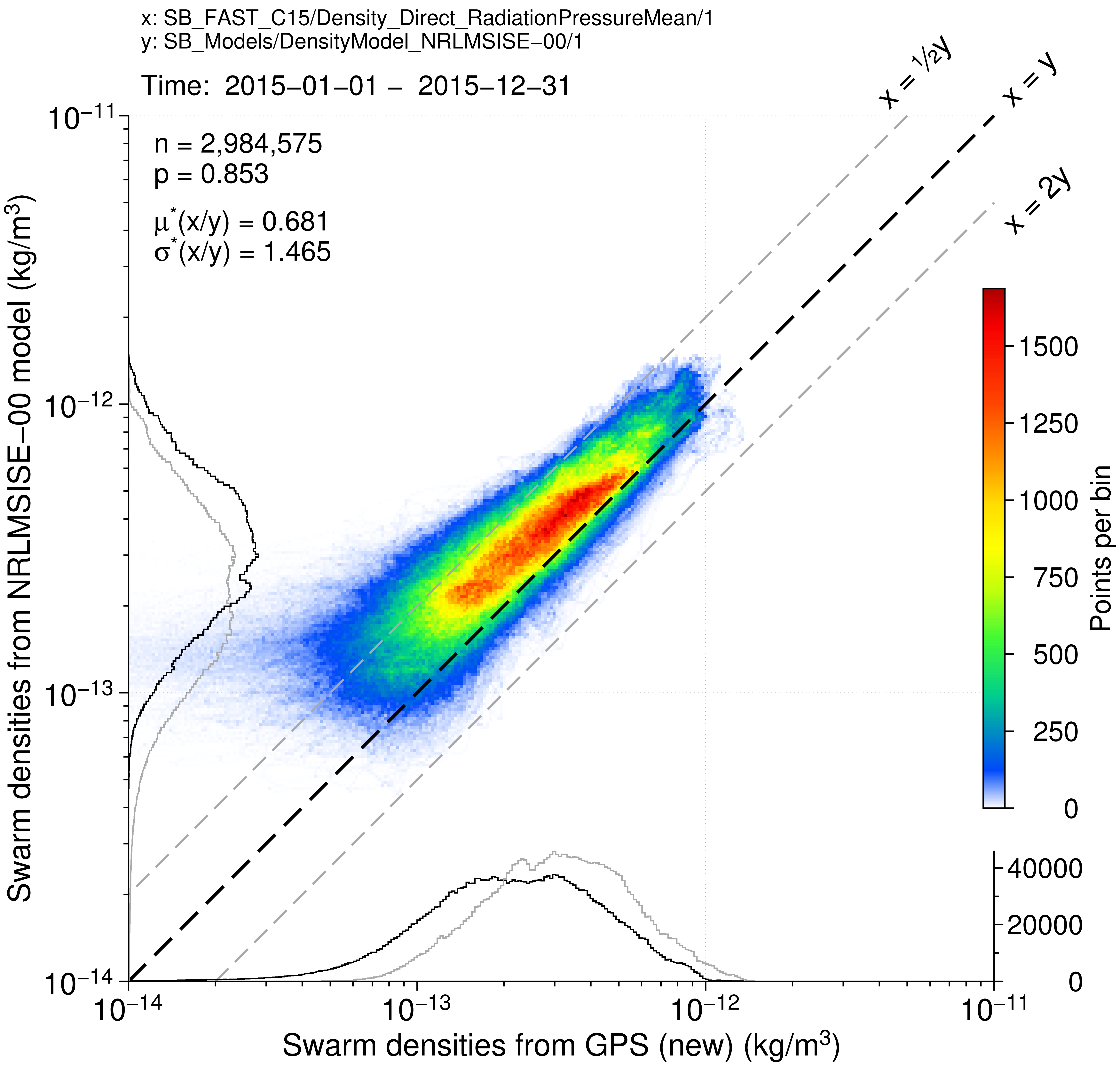


Swarm C GPS-derived density data (FAST C15)
Argument of latitude (deg)
360
270
180
90
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^{-12} kg/m^3
Swarm C field-aligned current density
Argument of latitude (deg)
8
6
4
2
0
−2
−4
−6
−8
μA/m^2
ap (nT), $F_{10.7}$ (sfu)
200
100
0
100
0
−100
−200
SYM-H index (nT)
15
16
17
18
19
20
March 2015

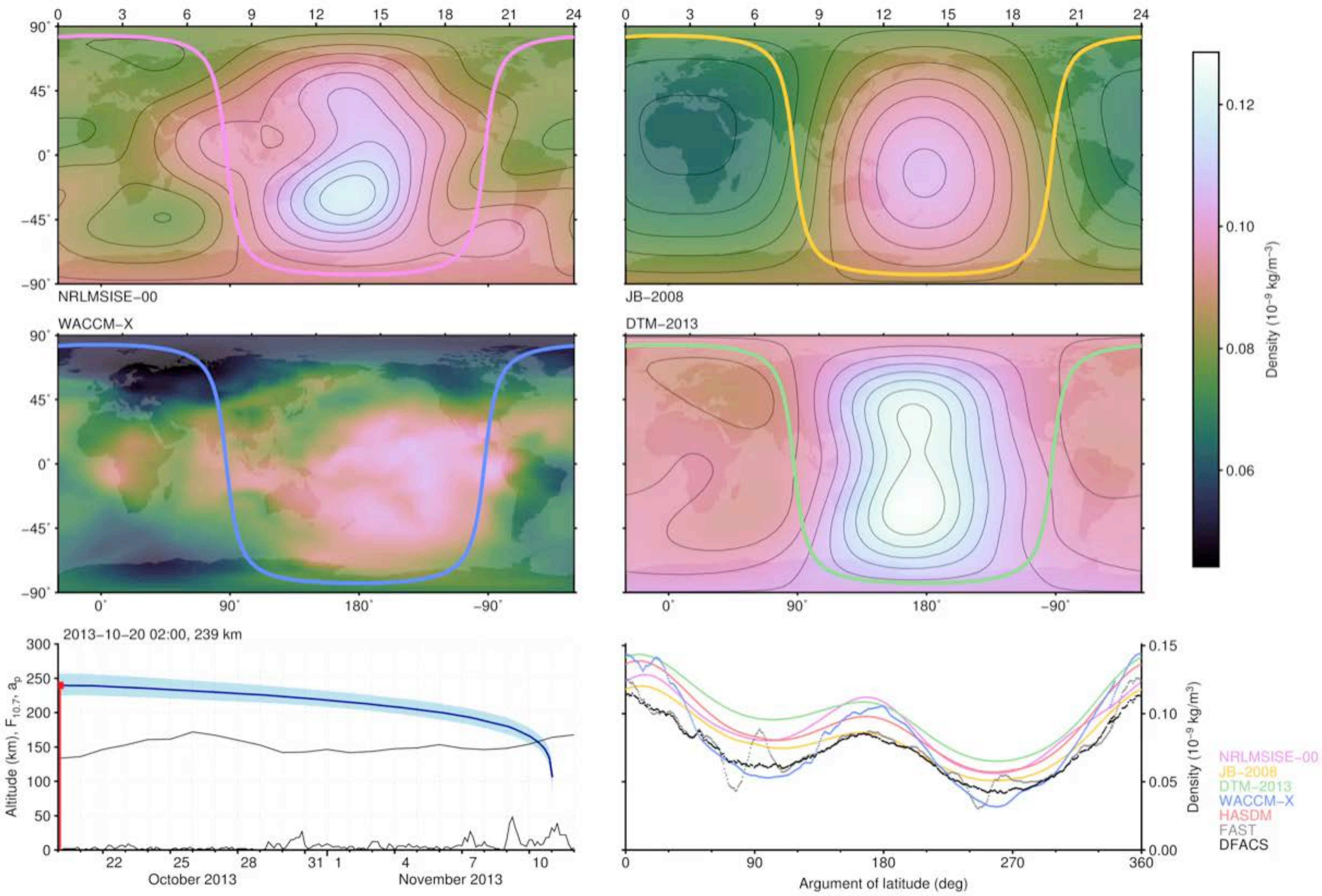
Swarm data/model comparisons



x: SC_FAST_C15/Density_Direct_RadiationPressureMean/1
y: SC_Models/DensityModel_NRLMSISE−00/1
Time: 2015−01−01 − 2015−12−31
n = 3,134,423
p = 0.906
μ*(x/y) = 0.688
σ*(x/y) = 1.272
x = ½y
x = y
x = 2y
Points per bin
2000
1000
0
60000
40000
20000
0
10−11
10−12
10−13
10−14
Swarm densities from NRLMSISE−00 model (kg/m3)
Swarm densities from GPS FAST C15 (kg/m3)


x: SB_FAST_C15/Density_Direct_RadiationPressureMean/1
y: SB_Models/DensityModel_NRLMSISE-00/1
Time: 2015–01–01 – 2015–12–31
n = 2,984,575
p = 0.853
$\mu^*(x/y) = 0.681$
$\sigma^*(x/y) = 1.465$
$x = \frac{1}{2}y$
$x = y$
$x = 2y$
Points per bin
Swarm densities from NRLMSISE–00 model (kg/m^3)
Swarm densities from GPS (new) (kg/m^3)

GOCE re-entry



NRLMSISE-00
JB-2008
WACCM-X
DTM-2013
Density (10^{-9} kg/m^3)
2013-10-20 02:00, 239 km
Altitude (km), $F_{10.7}$, a_p
October 2013
November 2013
Argument of latitude (deg)
NRLMSISE-00
JB-2008
DTM-2013
WACCM-X
HASDM
FAST
DFACS

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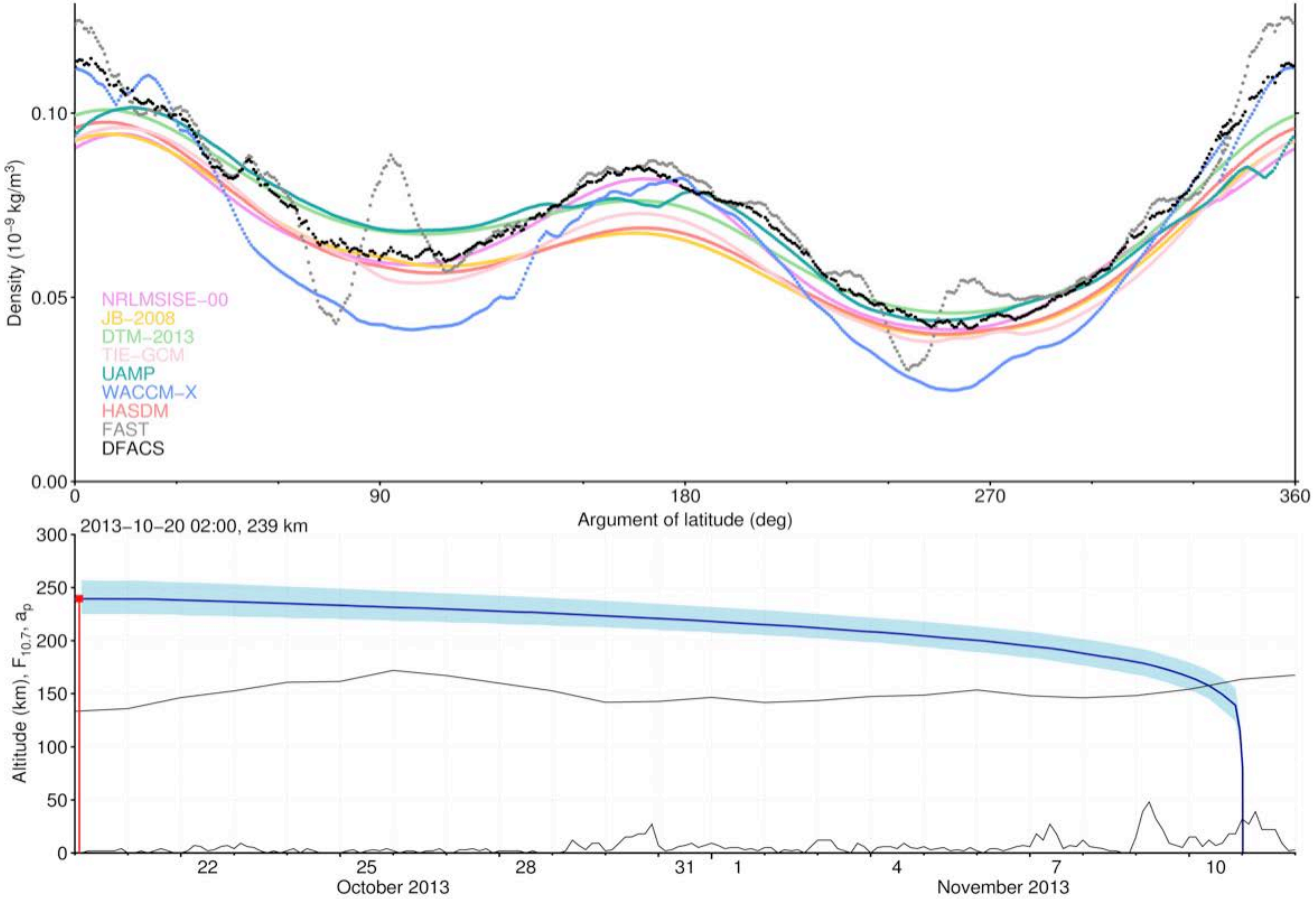

Density (10^{-9} kg/m^3)
0.10
0.05
0.00
NRLMSISE-00
JB-2008
DTM-2013
TIE-GCM
UAMP
WACCM-X
HASDM
FAST
DFACS
0
90
180
270
360
Argument of latitude (deg)
2013-10-20 02:00, 239 km
Altitude (km), $F_{10.7}$, a_p
300
250
200
150
100
50
0
22
25
28
31
1
4
7
10
October 2013
November 2013

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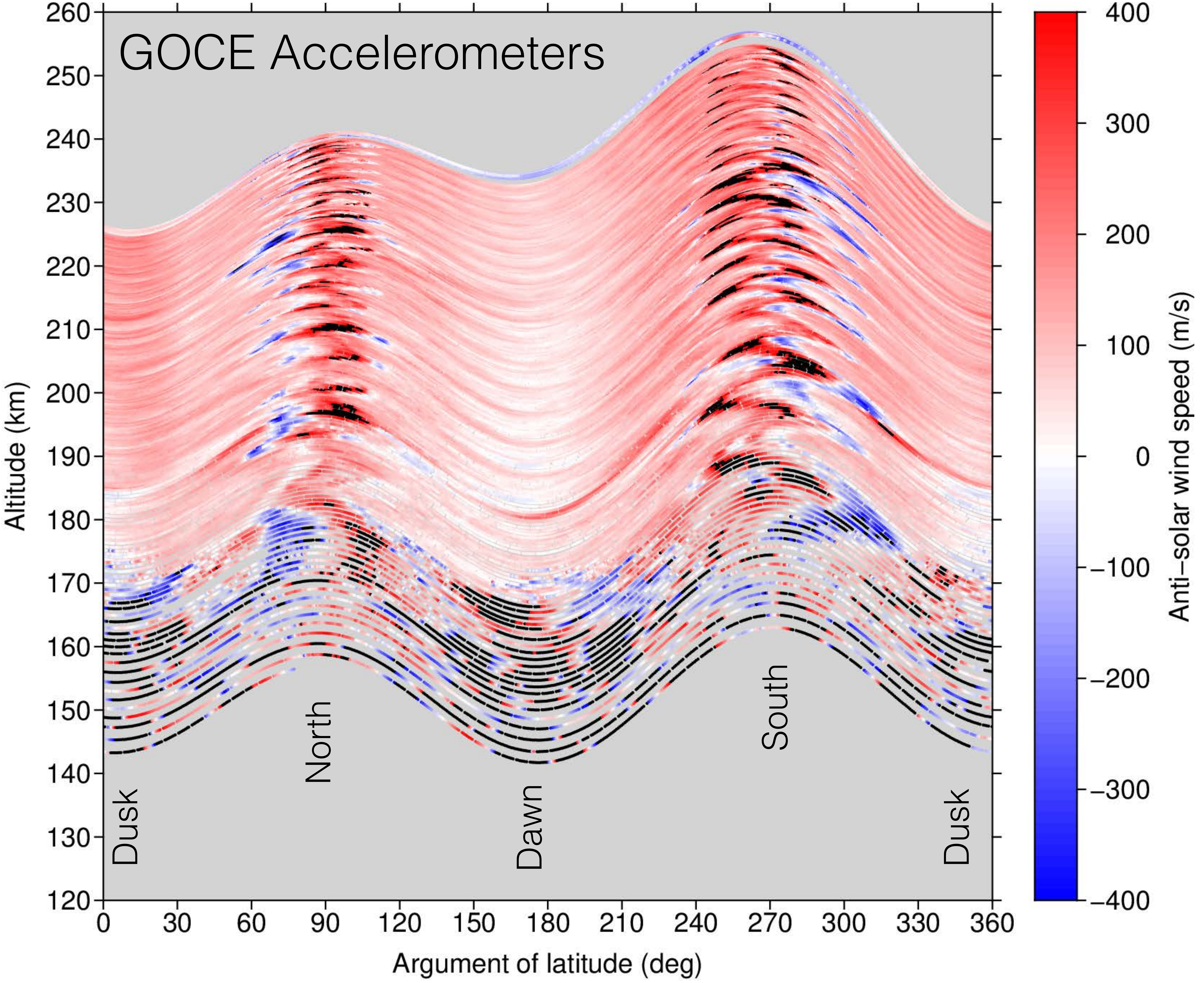
October 22, 2013

November 9, 2013

November 10, 2013

November 11, 2013

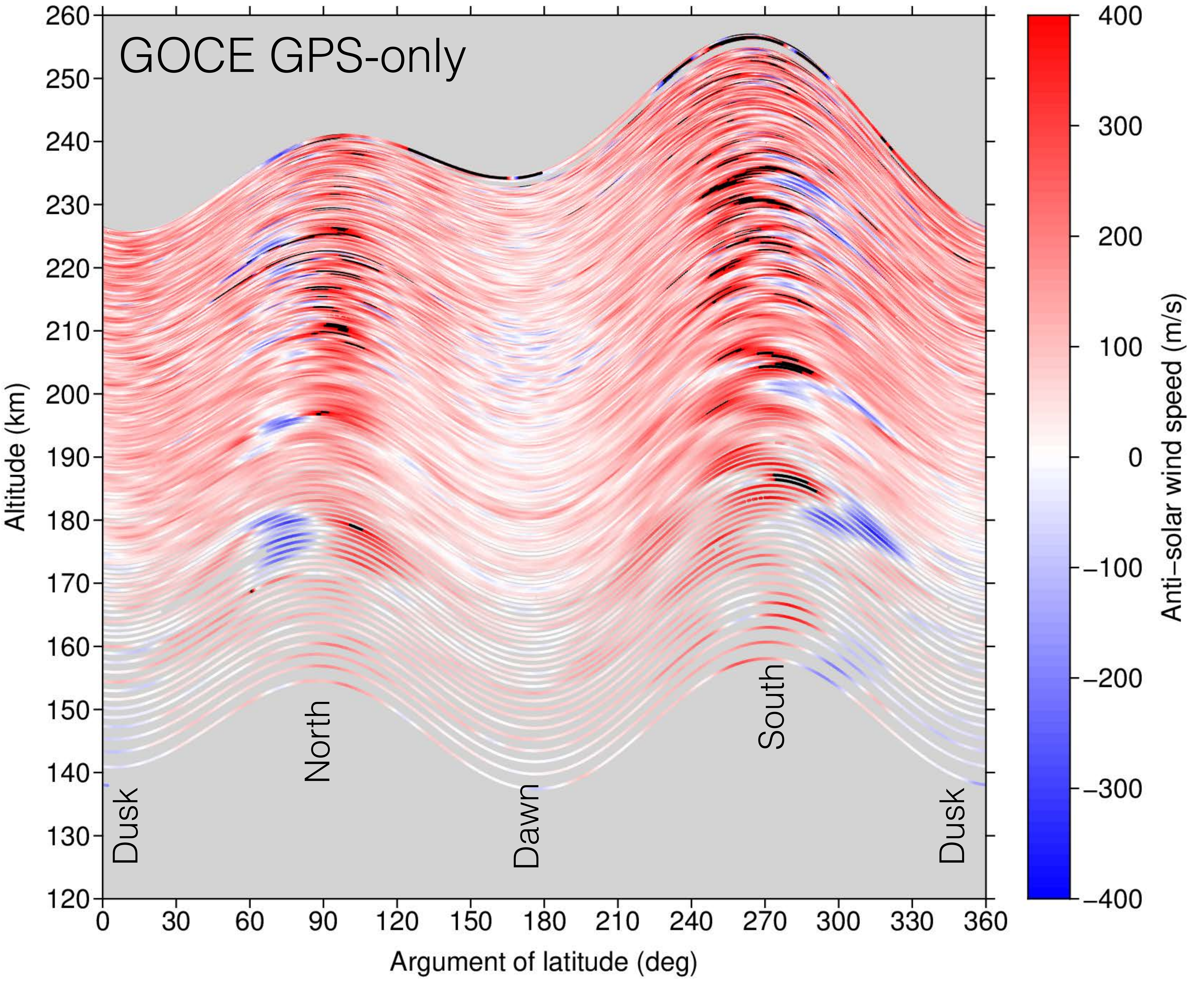


October 22, 2013

November 9, 2013

November 10, 2013

November 11, 2013




GOCE data (patched GPS+ACC)
HWM14
Altitude (km)
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
0
30
60
90
120
150
180
210
240
270
300
330
360
Argument of latitude (deg)
Argument of latitude (deg)
400
300
200
100
0
−100
−200
−300
−400
Anti−solar wind speed (m/s)

GOCE data
TIE-GCM
Altitude (km)
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
0
30
60
90
120
150
180
210
240
270
300
330
360
Argument of latitude (deg)
Argument of latitude (deg)
Anti–solar wind speed (m/s)
400
300
200
100
0
−100
−200
−300
−400

Other work in progress

- Routine Swarm processing with 2-4 weeks latency, data set user manual (this summer)
- Use of high-fidelity geometry models (to be implemented this summer for Swarm)
- GOCE vertical wind data set (this year)
- GOCE torque derived density/wind, for self consistent aerodynamic model parameter determination (this year)
- Complete reprocessing of CHAMP, GRACE, GOCE and Swarm data using updated aerodynamic models, improved consistency (next year)

Outlook / wish list

- Process GRACE-FO, MicroSCOPE data
- Low latency / near real-time thermosphere data availability for density model data assimilation
- Improve access to users
- Open up new investigations: use data to improve both satellite aerodynamic and thermosphere models, investigate long-term change in the thermosphere, investigate synergy with ICON and GOLD, etc.