Satellite aerodynamics and thermosphere dynamics

investigations with GOCE and Swarm

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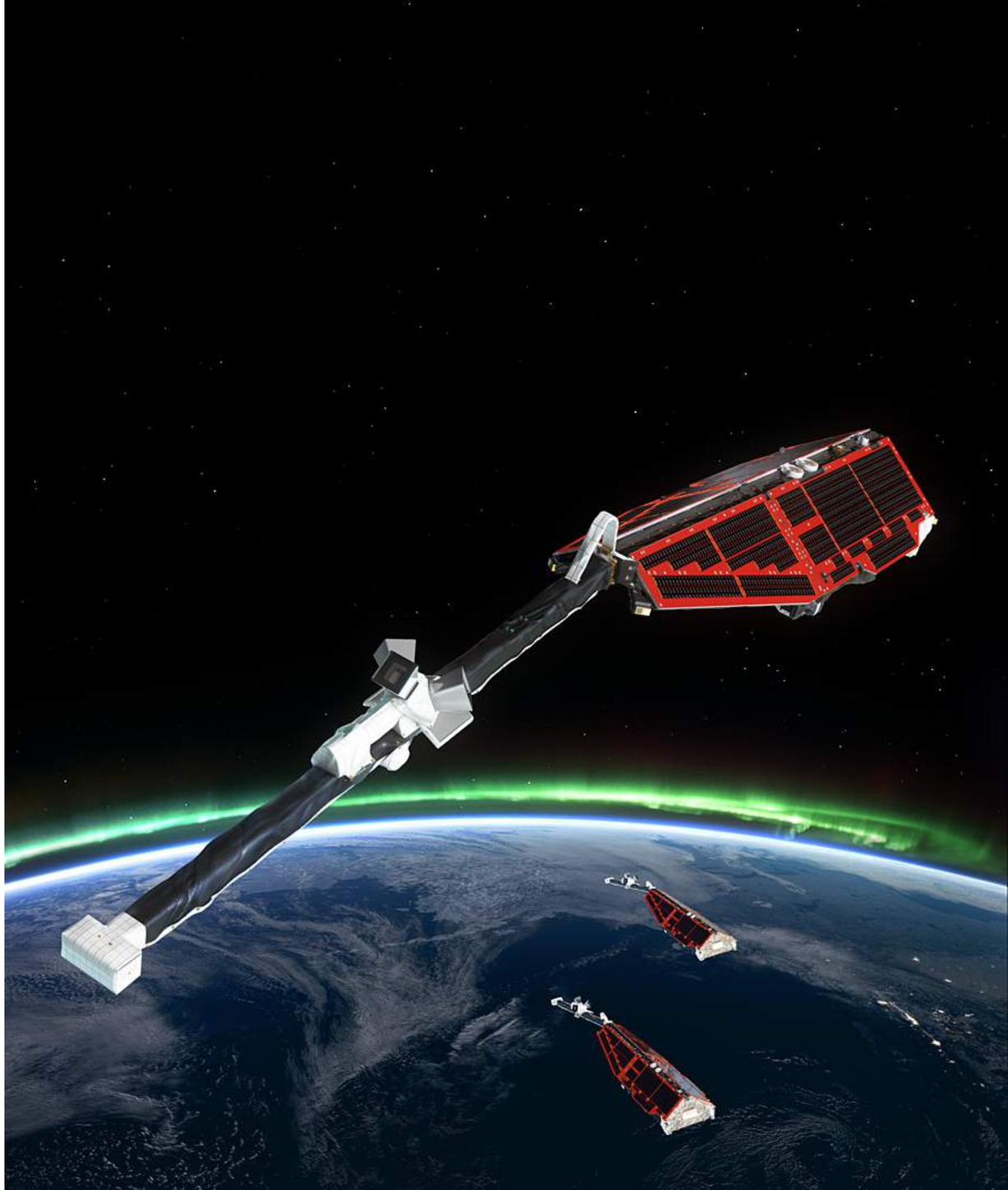
(Starting at KNMI in Feb 2019)

Discoverer - 28 November 2018, Munich, Germany



Contents

- Introduction
- Satellite missions and orbits
- Measurement principles and processing algorithms
- Space weather in the thermosphere
- Uncertainty in satellite aerodynamics and the scale of the thermosphere
- GOCE re-entry special dataset
- Conclusions

Satellite missions and orbits

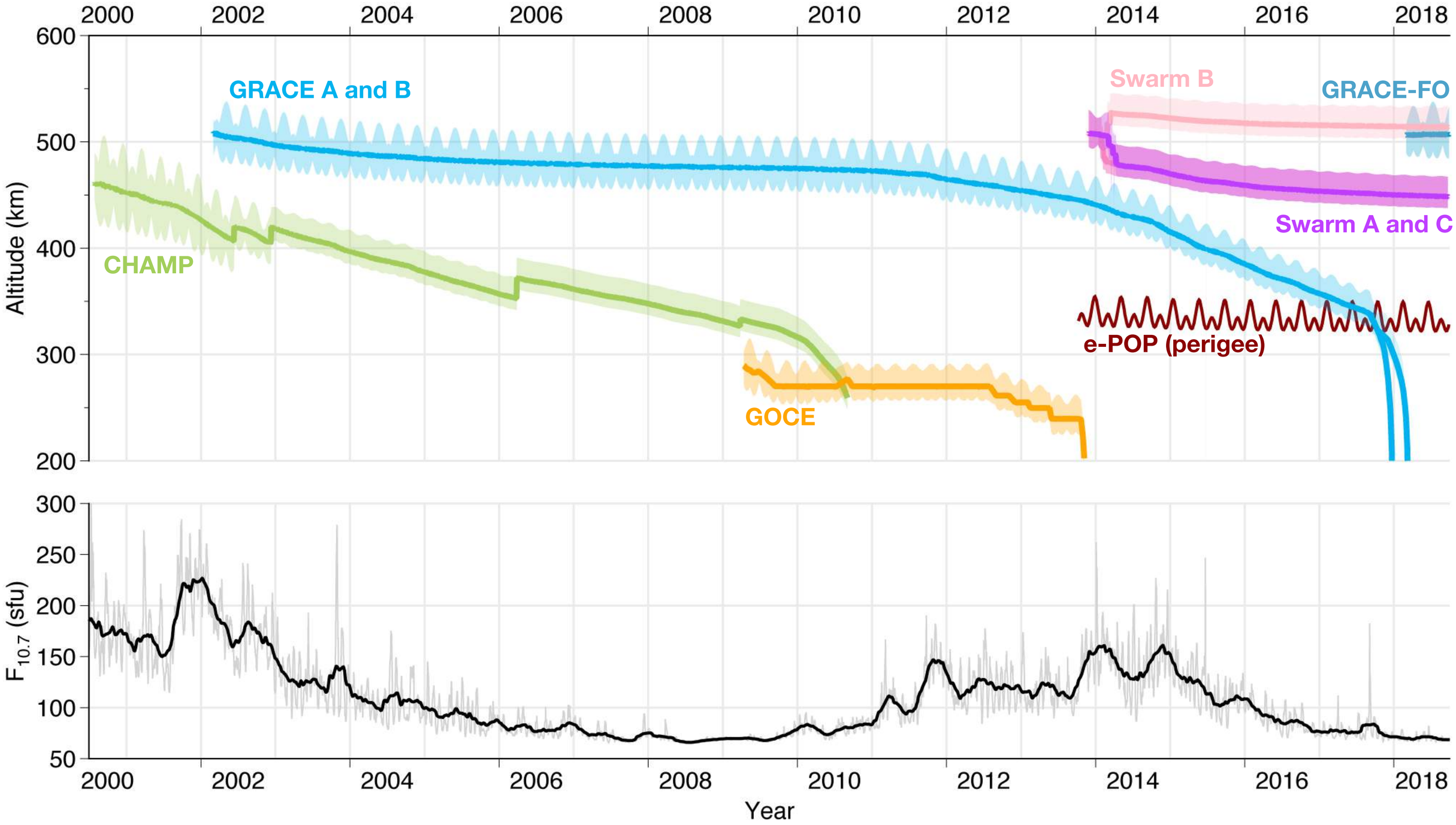
CHAMP

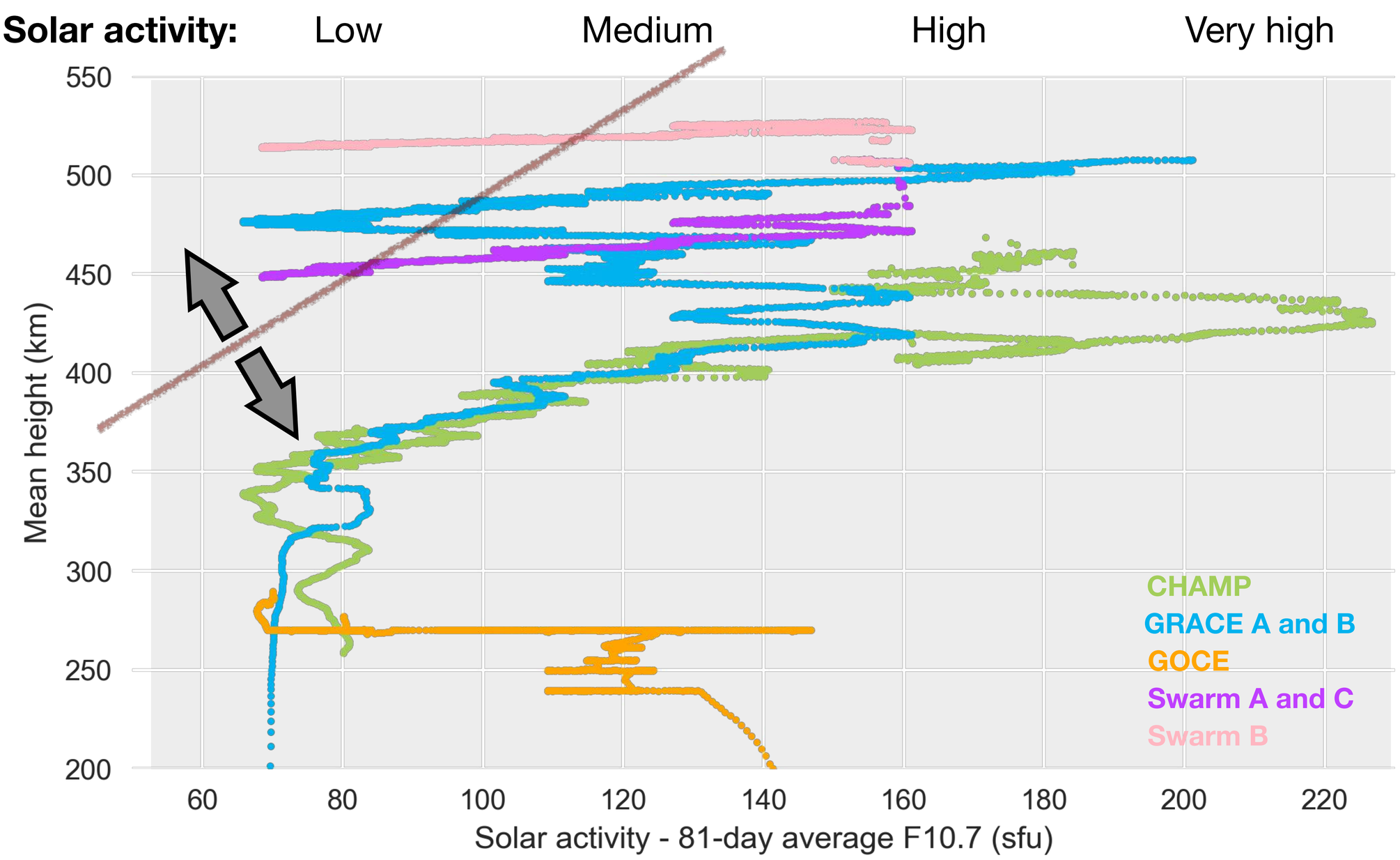
GRACE

GOCE

Swarm

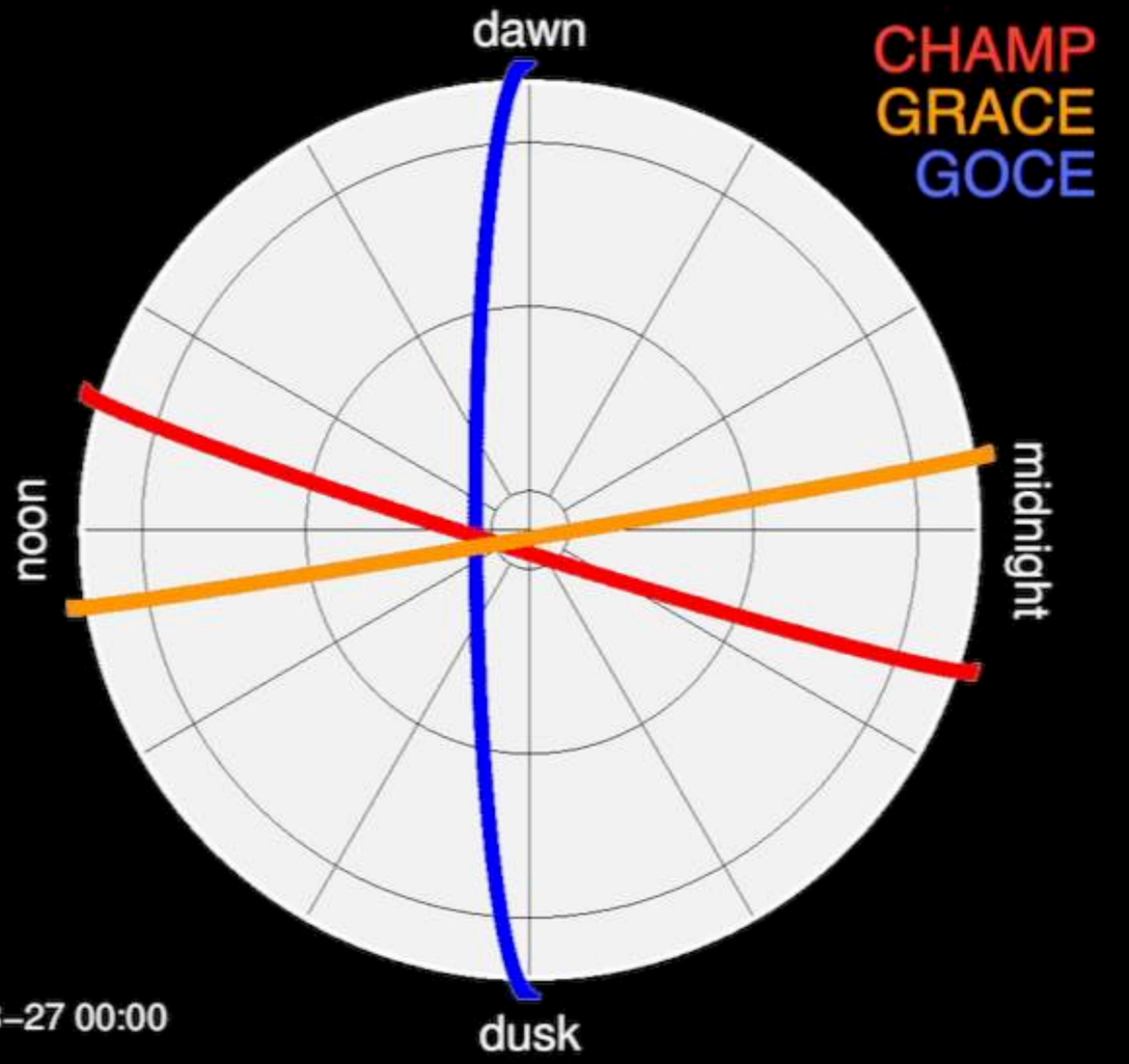
GRACE Follow-On


2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
600
500
400
300
200
Altitude (km)
GRACE A and B
Swarm B
GRACE-FO
Swarm A and C
CHAMP
e-POP (perigee)
GOCE
300
250
200
150
100
50
$F_{10.7}$ (sfu)
Year


Solar activity:
Low
Medium
High
Very high
550
500
450
400
350
300
250
200
Mean height (km)
60
80
100
120
140
160
180
200
220
Solar activity - 81-day average F10.7 (sfu)
CHAMP
GRACE A and B
GOCE
Swarm A and C
Swarm B

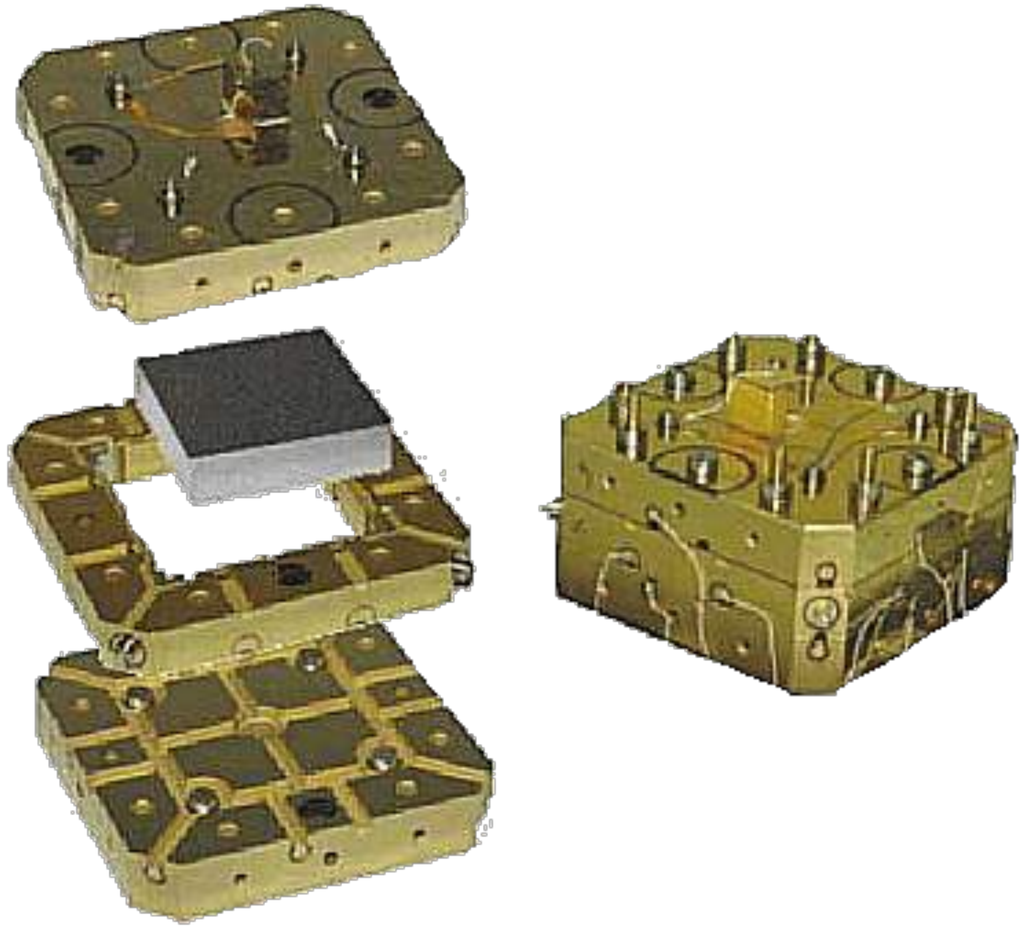
TU Delft

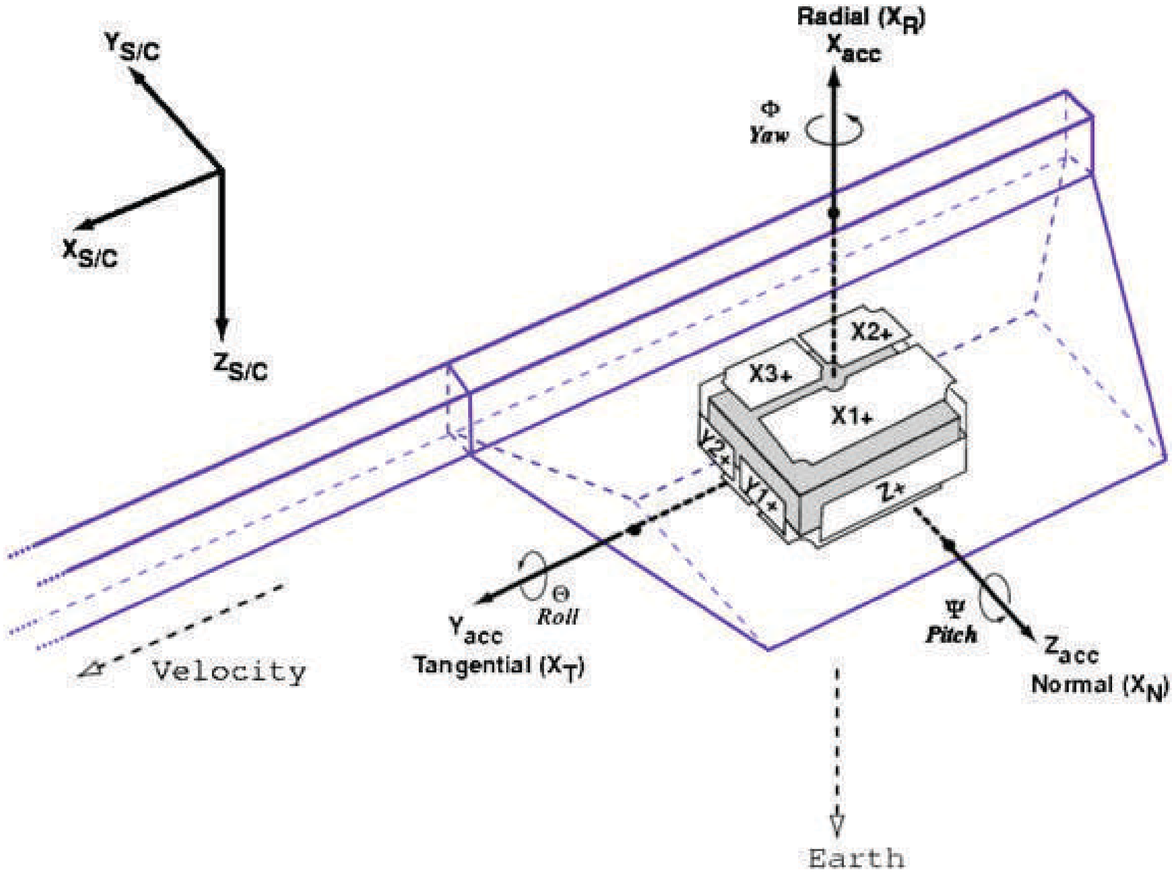
Orbit planes of CHAMP, GRACE and GOCE
view of the Northern Hemisphere



Measurement principle and processing algorithm

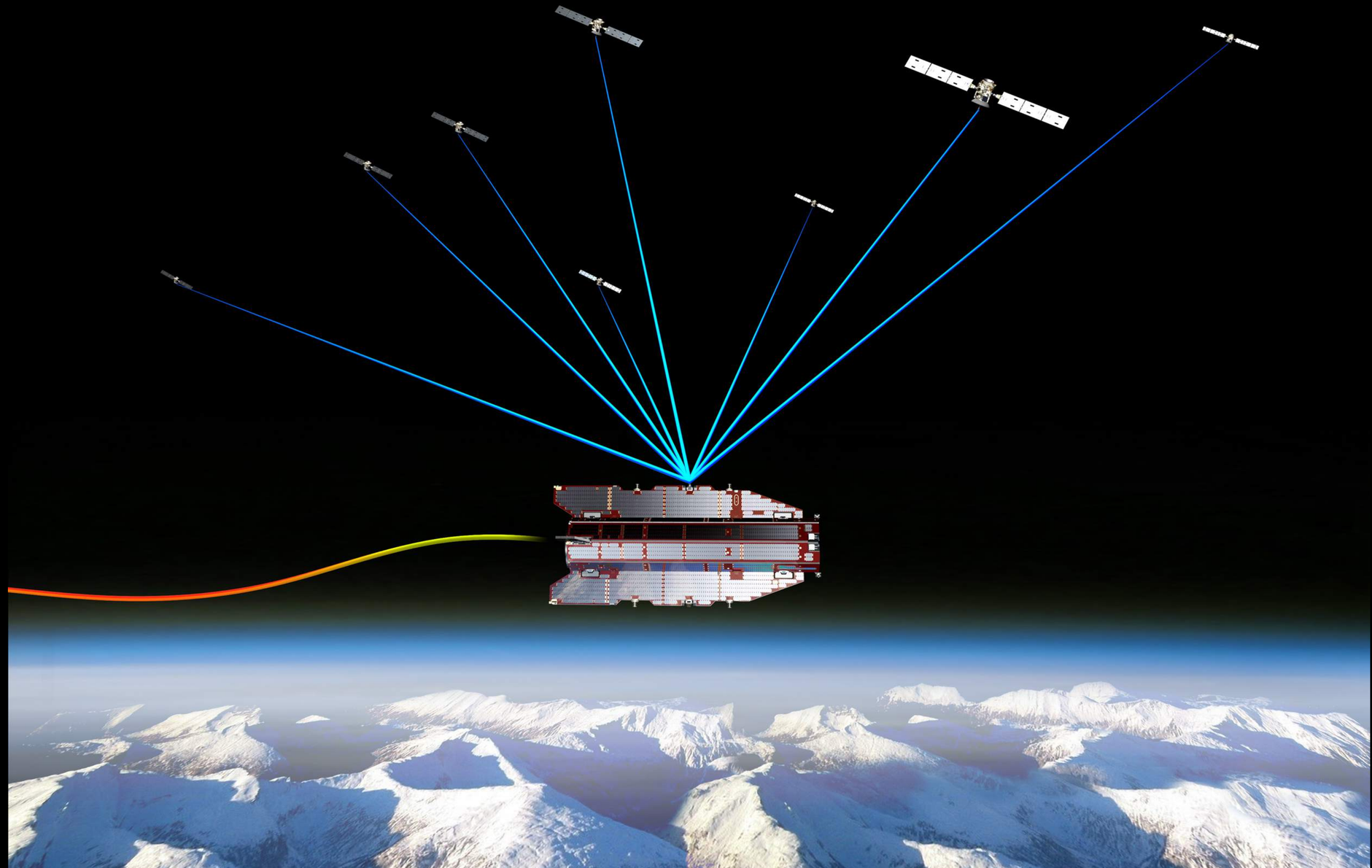
Accelerometer measurement principle



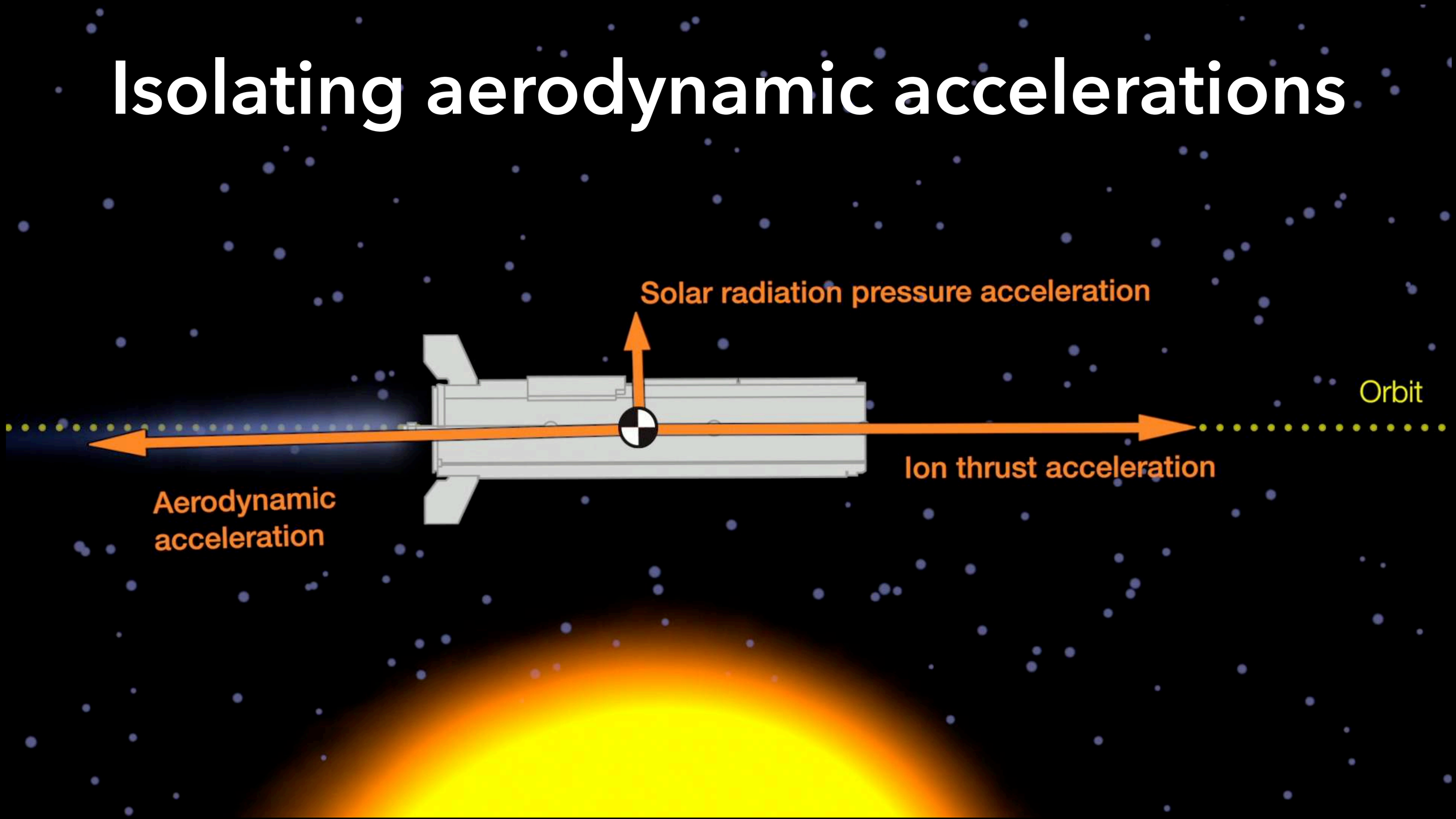


Figures: GFZ-Potsdam / CNES / ONERA

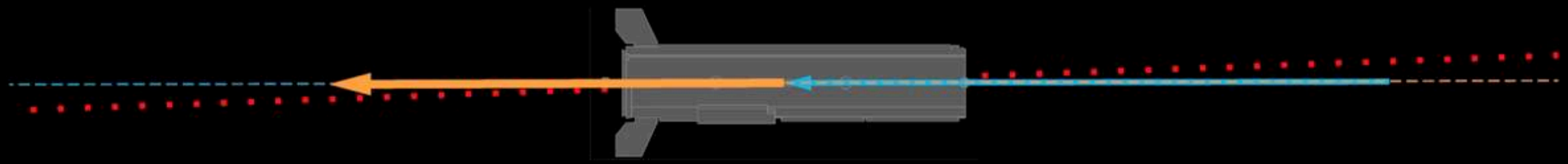
GPS acceleration measurement principle



Isolating aerodynamic accelerations



From aerodynamic accelerations to density and wind



Relative velocity of atmosphere

Satellite aerodynamic model:
- Geometry
- Gas-surface interaction

Modeled acceleration

Density model (e.g. NRLMSISE-00)

Sentman's exact theory for diffuse reflection of gas particles on a surface

$$C_{\mathrm{D},i,j} = \left[\frac{P_{i,j}}{\sqrt{\pi}} + \gamma_i Q_j Z_{i,j} + \frac{\gamma_i}{2}\frac{v_{\mathrm{re}}}{v_{\mathrm{inc}}}\left(\gamma_i\sqrt{\pi}Z_{i,j} + P_{i,j}\right)\right]\frac{A_i}{A_{\mathrm{ref}}}$$

$$C_{\mathrm{L},i,j} = \left[l_i G_j Z_{i,j} + \frac{l_i}{2}\frac{v_{\mathrm{re}}}{v_{\mathrm{inc}}}\left(\gamma_i\sqrt{\pi}Z_{i,j} + P_{i,j}\right)\right]\frac{A_i}{A_{\mathrm{ref}}}$$

$$G_j = \frac{1}{2S_j^2}, \quad P_{i,j} = \frac{1}{S_j}\exp(-\gamma_i^2 S_j^2), \quad Q_j = 1 + G_j, \quad Z_{i,j} = 1 + \mathrm{erf}(\gamma_i S_j)$$

$$\gamma_i = \cos(\theta_i) = -\hat{\boldsymbol{u}}_{\mathrm{D}} \cdot \hat{\boldsymbol{n}}_i, \quad l_i = -\hat{\boldsymbol{u}}_{\mathrm{L}} \cdot \hat{\boldsymbol{n}}_i$$

$$\frac{v_{\mathrm{re}}}{v_{\mathrm{inc}}} = \sqrt{\frac{1}{2}\left[1 + \alpha\left(\frac{4RT_{\mathrm{w}}}{v_{\mathrm{inc}}^2} - 1\right)\right]} \qquad S_j = \frac{v_{\mathrm{r}}}{c_{\mathrm{mp},j}} \qquad c_{\mathrm{mp},j} = \sqrt{2\frac{k}{m_j}T},$$

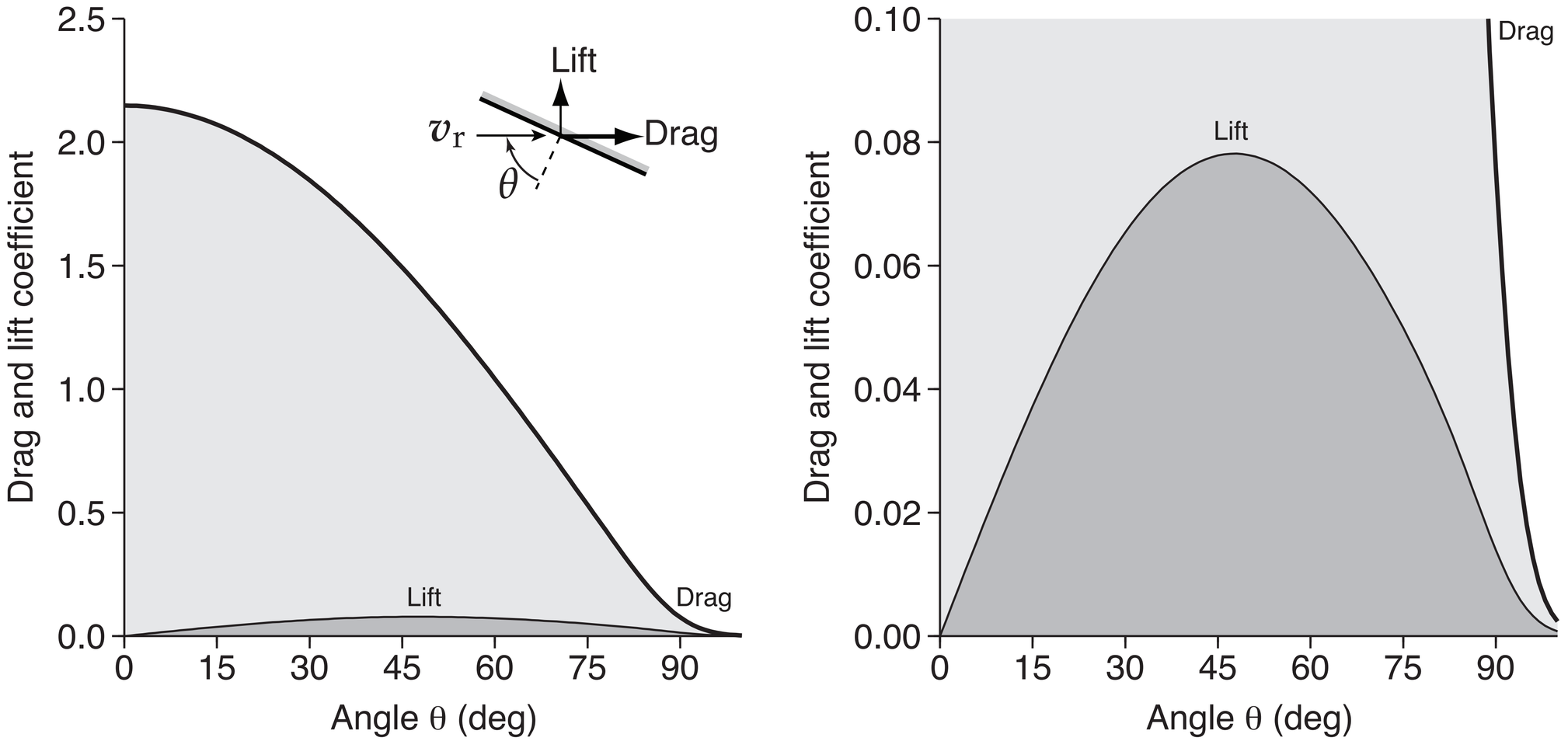
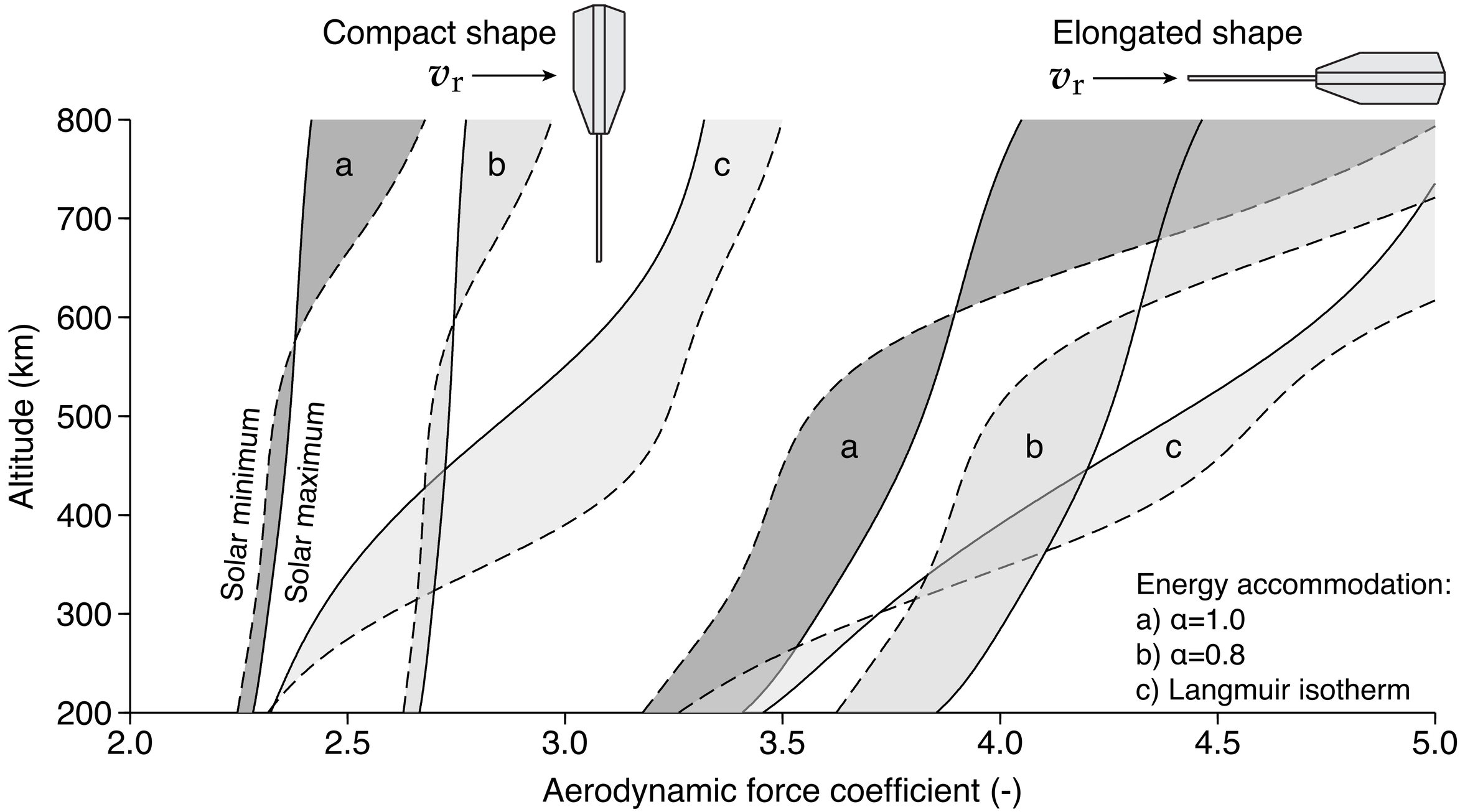
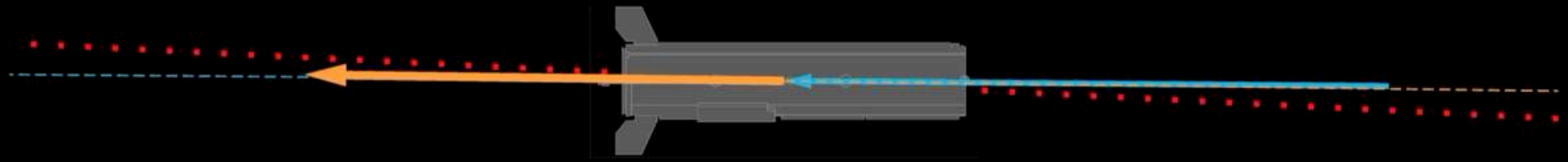


Figure 3.8 Drag and lift coefficients, according to Sentman's equations for a one-sided flat panel, as a function of the incidence angle θ. The right-hand plot contains the same information as the left-hand plot, but with a scaled Y-axis to more clearly show the lift and values around $\theta \approx 90°$.


Compact shape
v_r
Elongated shape
v_r
800
700
600
500
400
300
200
Altitude (km)
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Aerodynamic force coefficient (-)
a
b
c
Solar minimum
Solar maximum
a
b
c
Energy accommodation:
a) α=1.0
b) α=0.8
c) Langmuir isotherm

From aerodynamic accelerations to density and wind

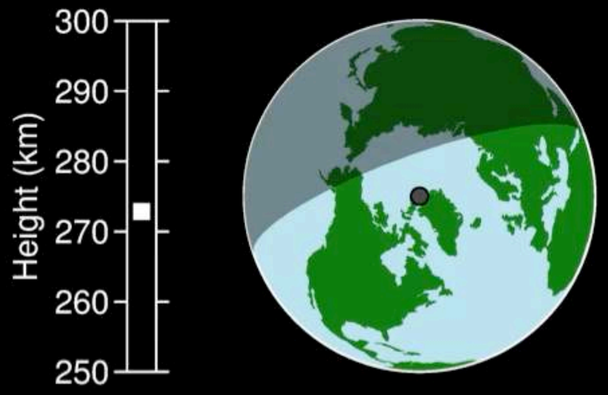


Relative velocity of atmosphere

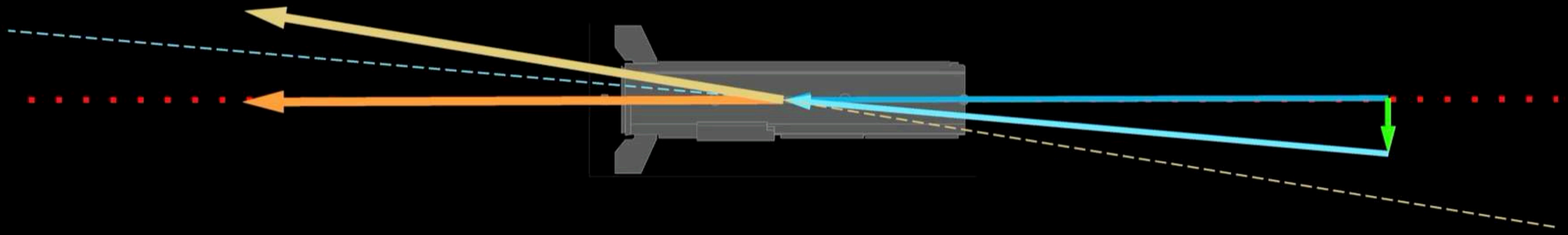
Satellite aerodynamic model:
- Geometry
- Gas-surface interaction

Modeled acceleration

Density model (e.g. NRLMSISE-00)



2010–04–05 15:20:00 GPS



Modeled acceleration (NRLMSISE-00, no wind)

Measured acceleration

Atmosphere velocity: orbit + corotation

Atmosphere velocity: orbit + corotation + crosswind

Crosswind velocity

Detailed satellite geometry models
PhD work Gunther March

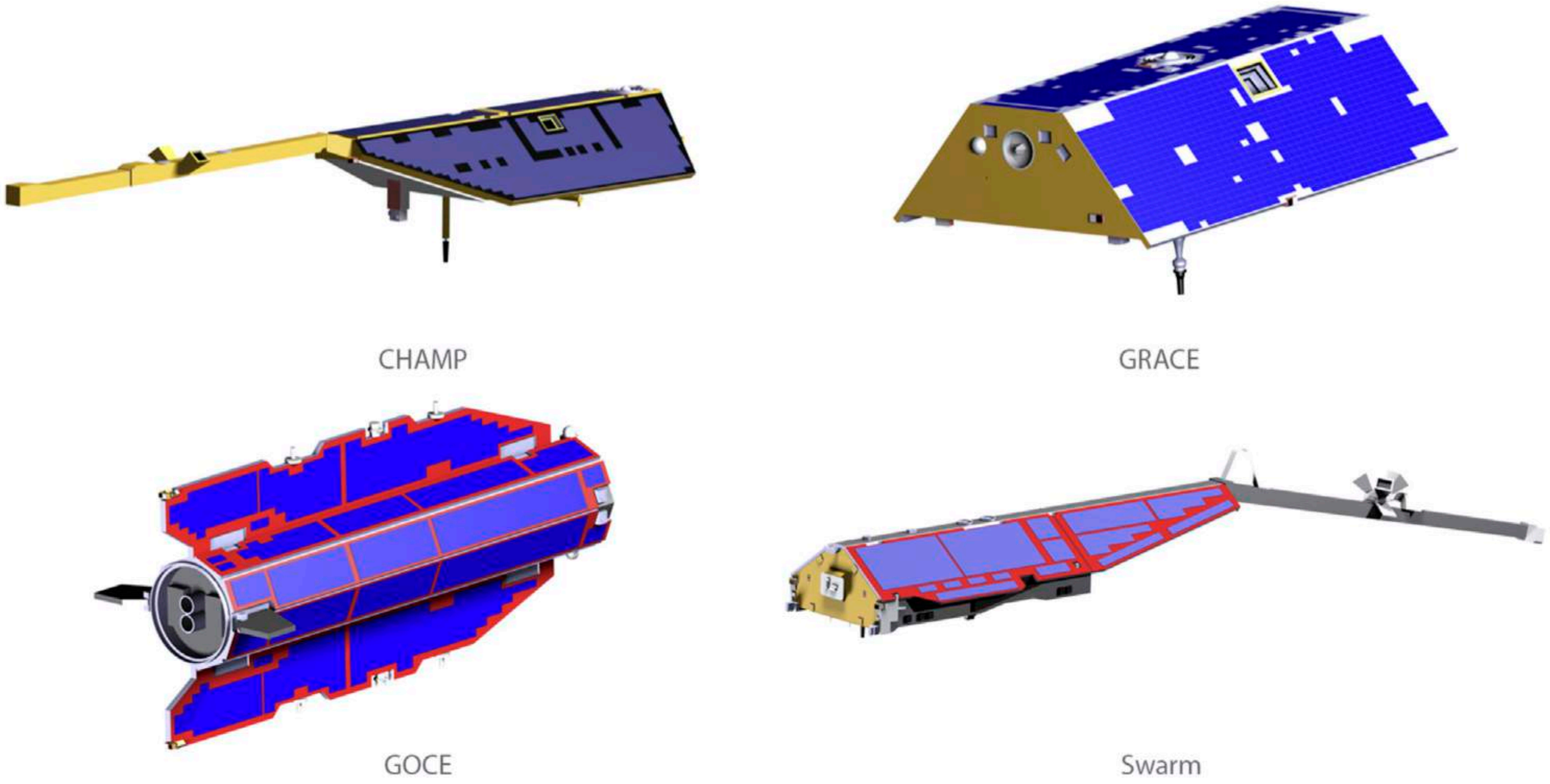
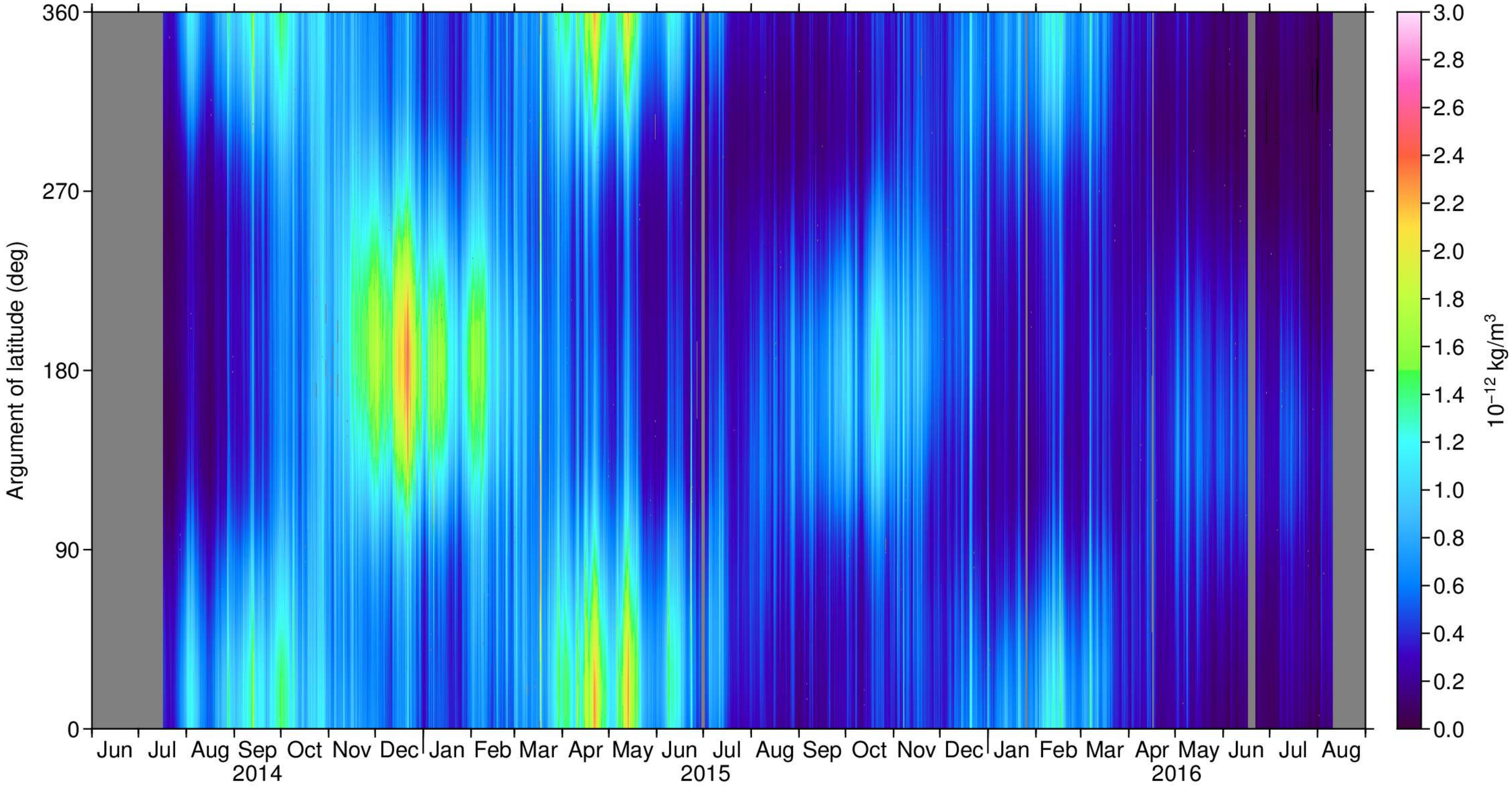
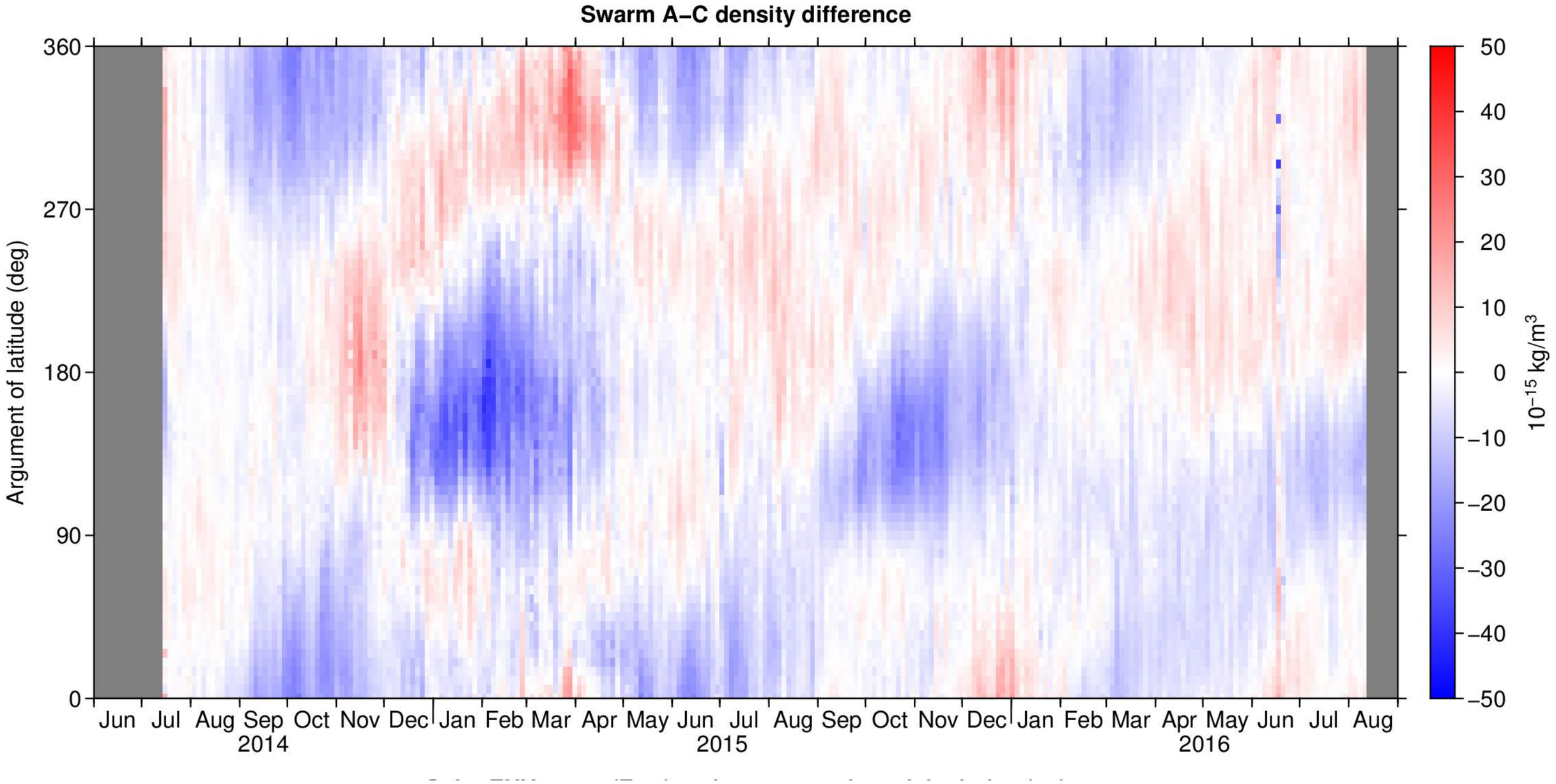
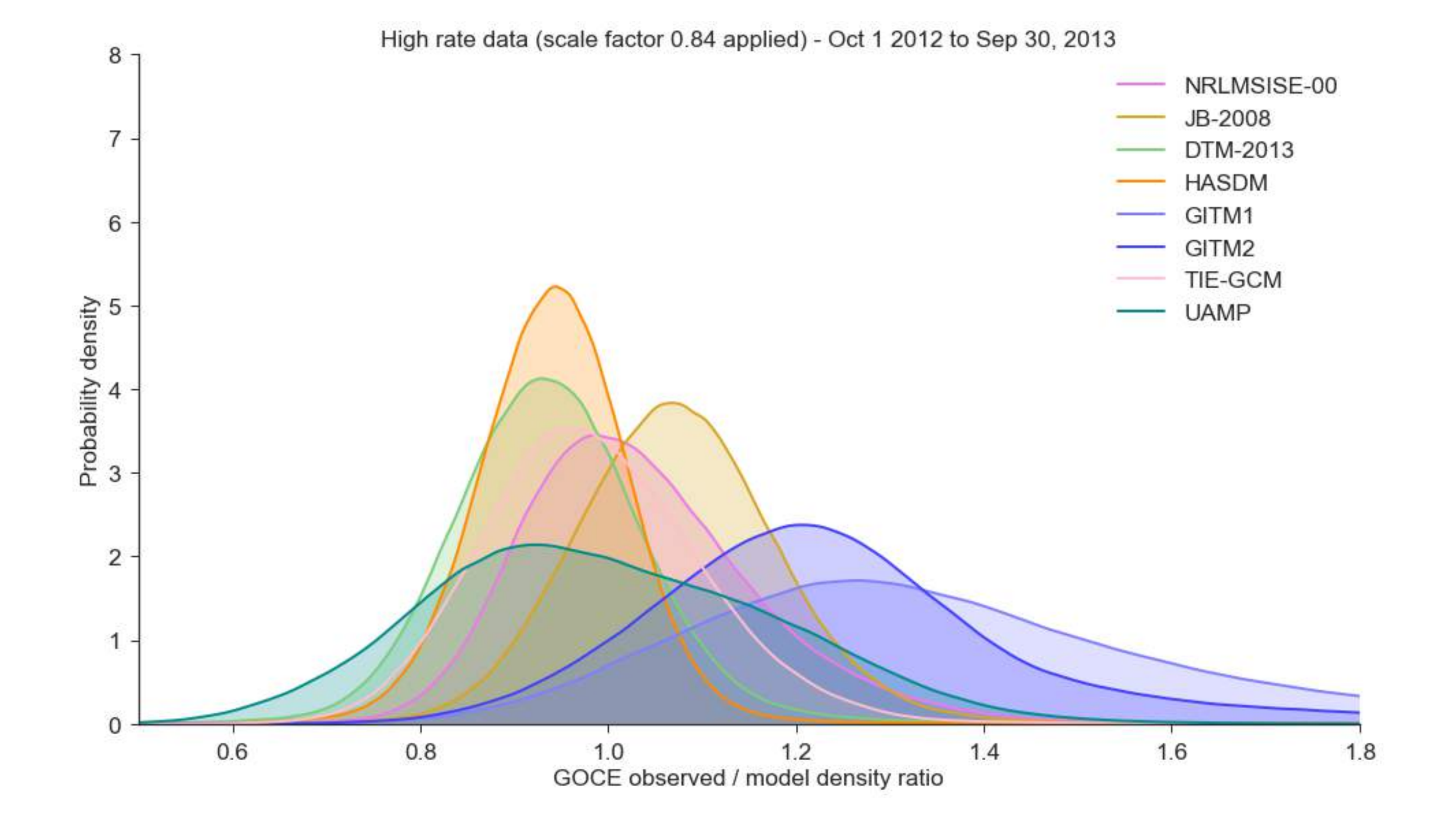


Fig. 2. Rendering of satellite geometry models designed with CATIA V5 R21.

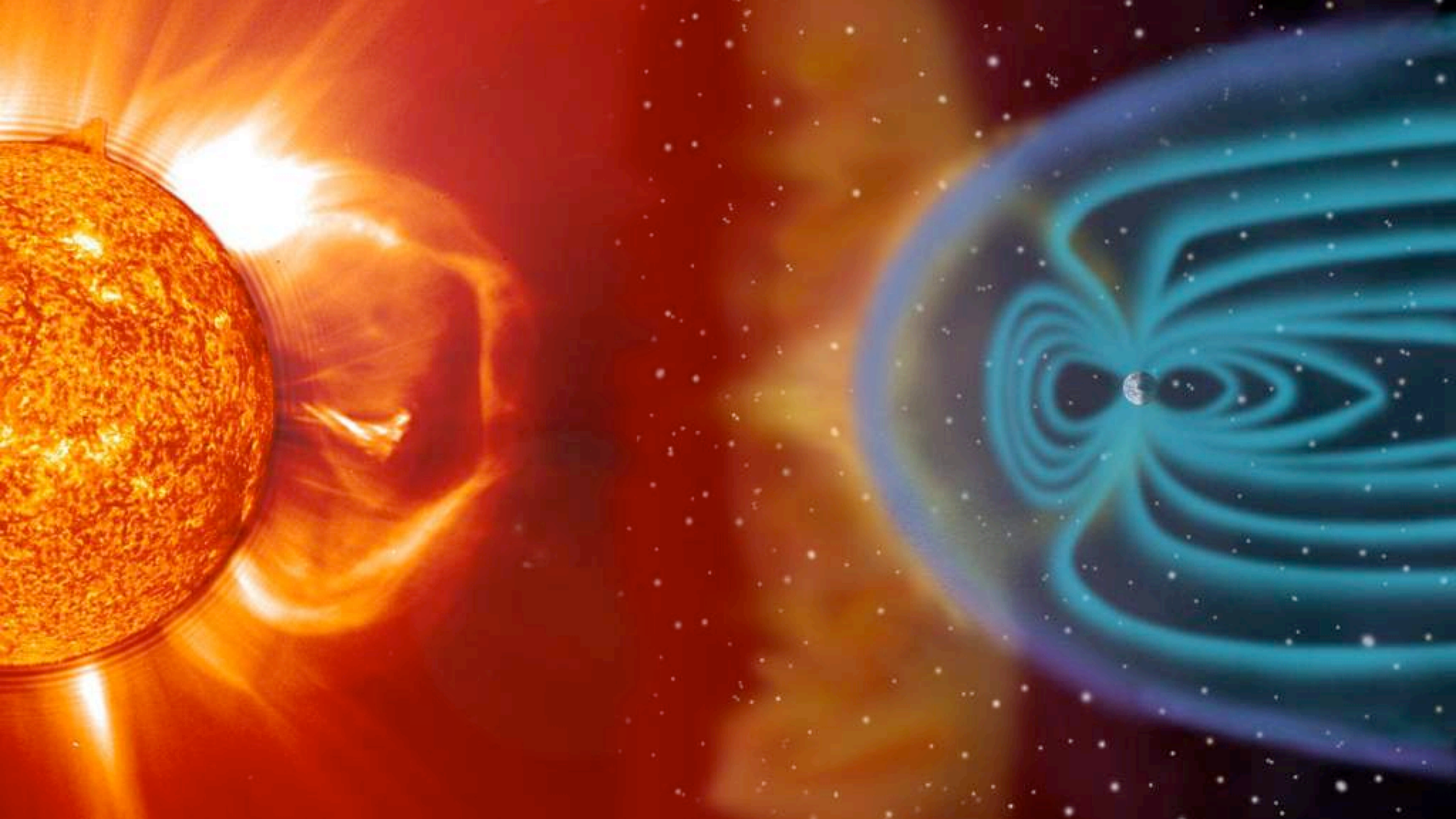
March, G., Doornbos, E. N., & Visser, P. N. A. M. (2018). High-fidelity geometry models for improving the consistency of CHAMP, GRACE, GOCE and Swarm thermospheric density data sets. Advances in Space Research. http://doi.org/10.1016/j.asr.2018.07.009

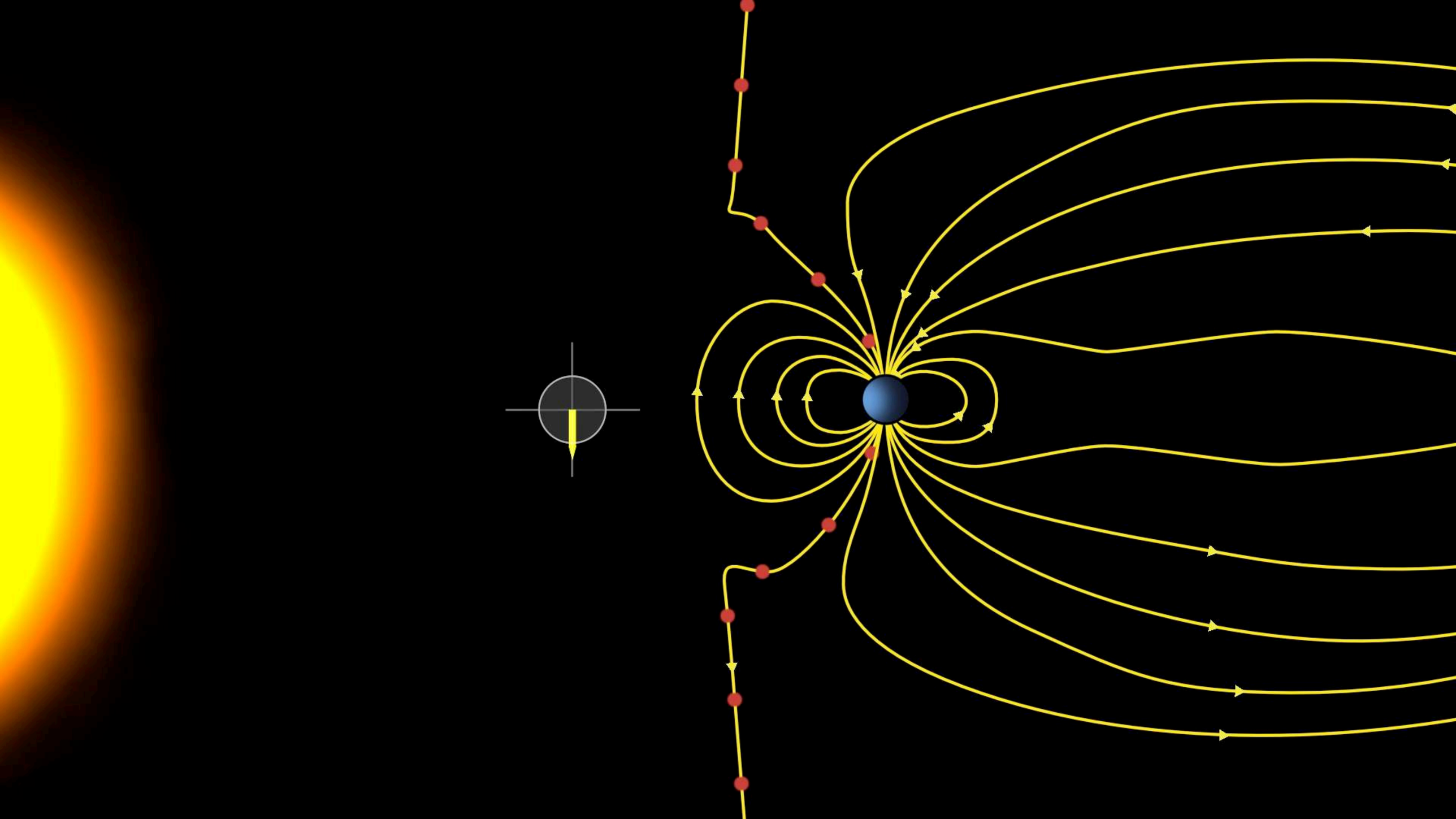

Swarm C GPS–derived density data (FAST C15)
Argument of latitude (deg)
360
270
180
90
0
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
2014
2015
2016
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10−12 kg/m3

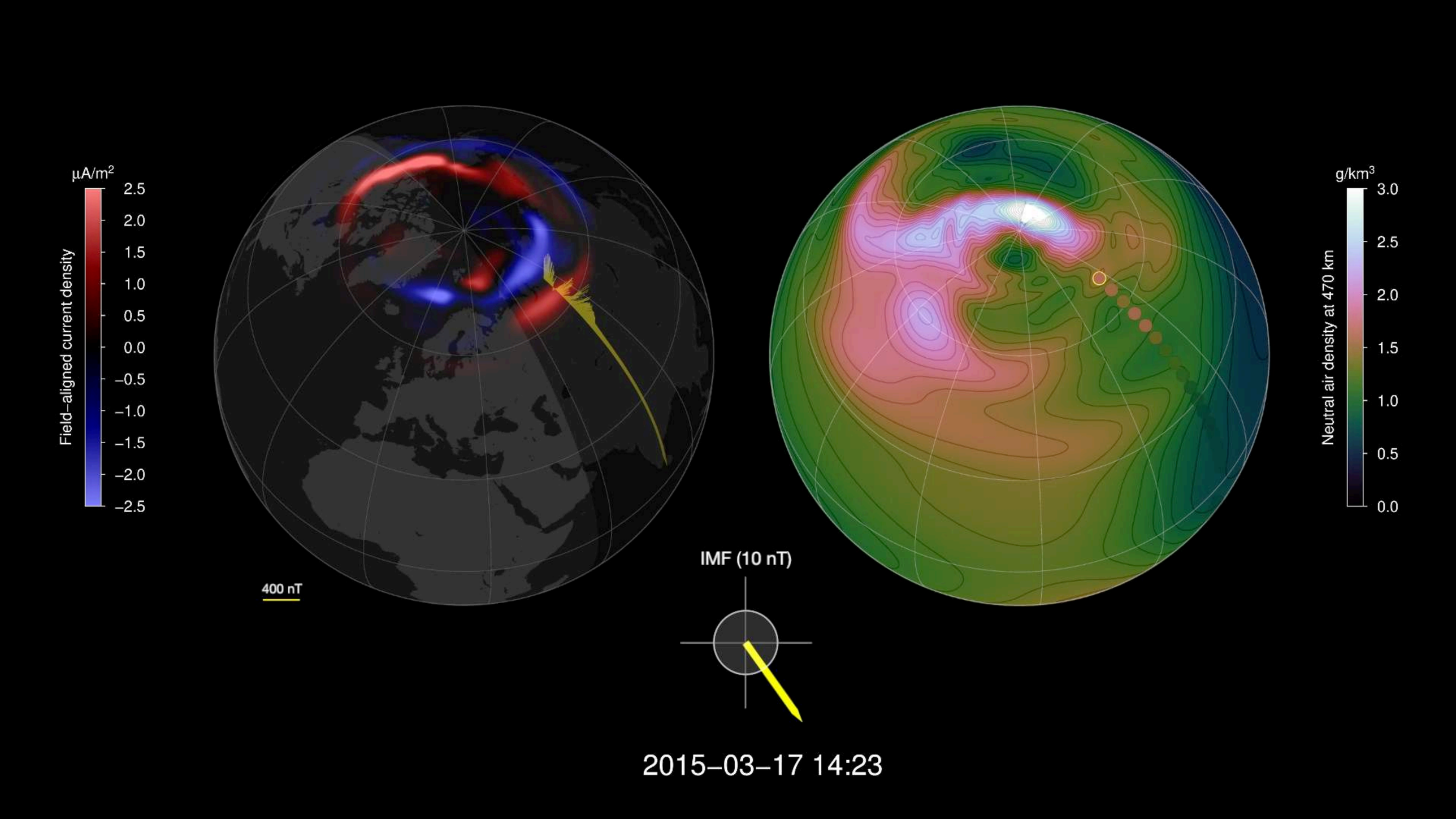

Swarm A–C density difference
Argument of latitude (deg)
360
270
180
90
0
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
2014
2015
2016
50
40
30
20
10
0
−10
−20
−30
−40
−50
10⁻¹⁵ kg/m³

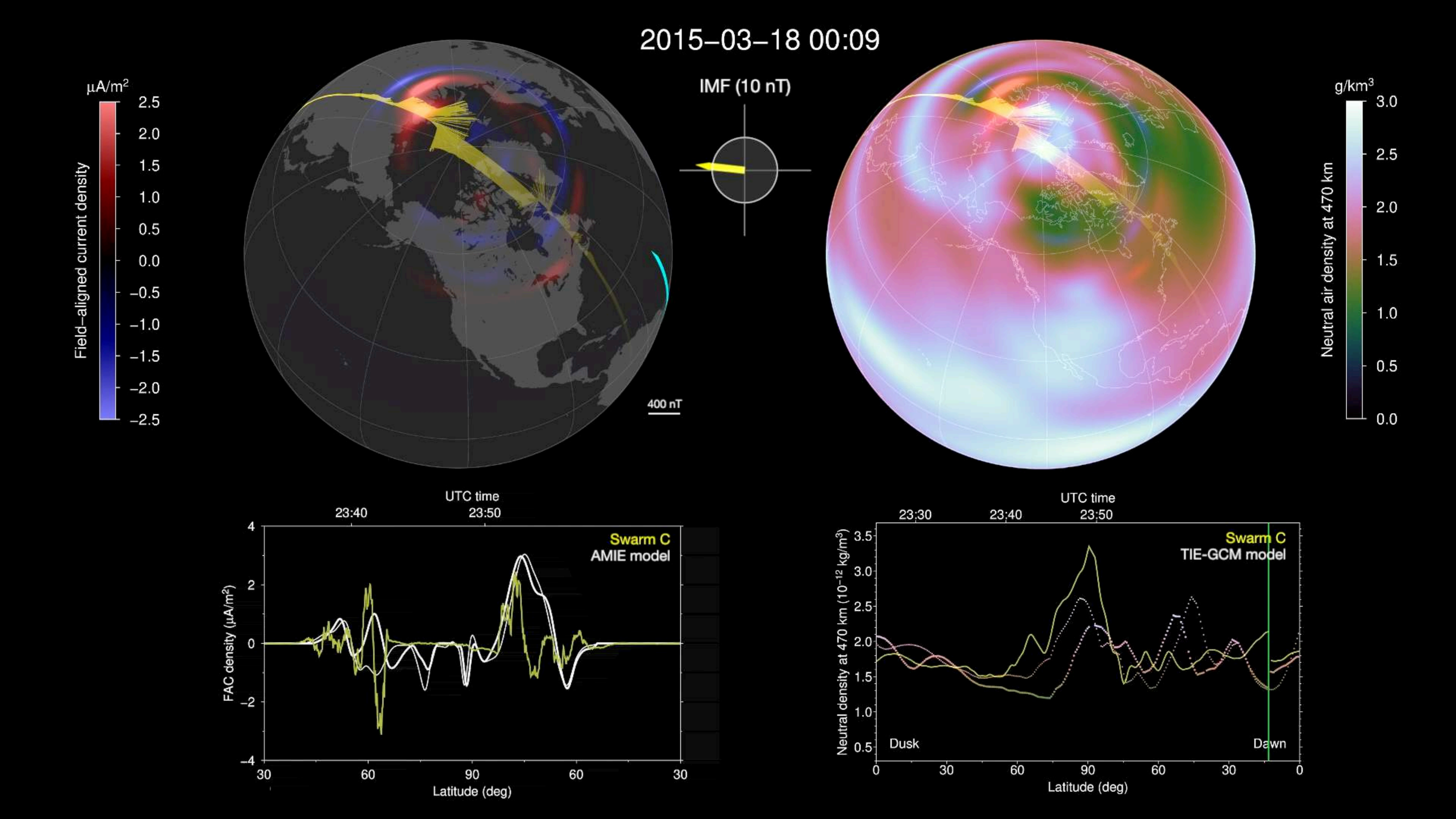

High rate data (scale factor 0.84 applied) - Oct 1 2012 to Sep 30, 2013
NRLMSISE-00
JB-2008
DTM-2013
HASDM
GITM1
GITM2
TIE-GCM
UAMP
Probability density
0
1
2
3
4
5
6
7
8
0.6
0.8
1.0
1.2
1.4
1.6
1.8
GOCE observed / model density ratio

Space weather in the thermosphere

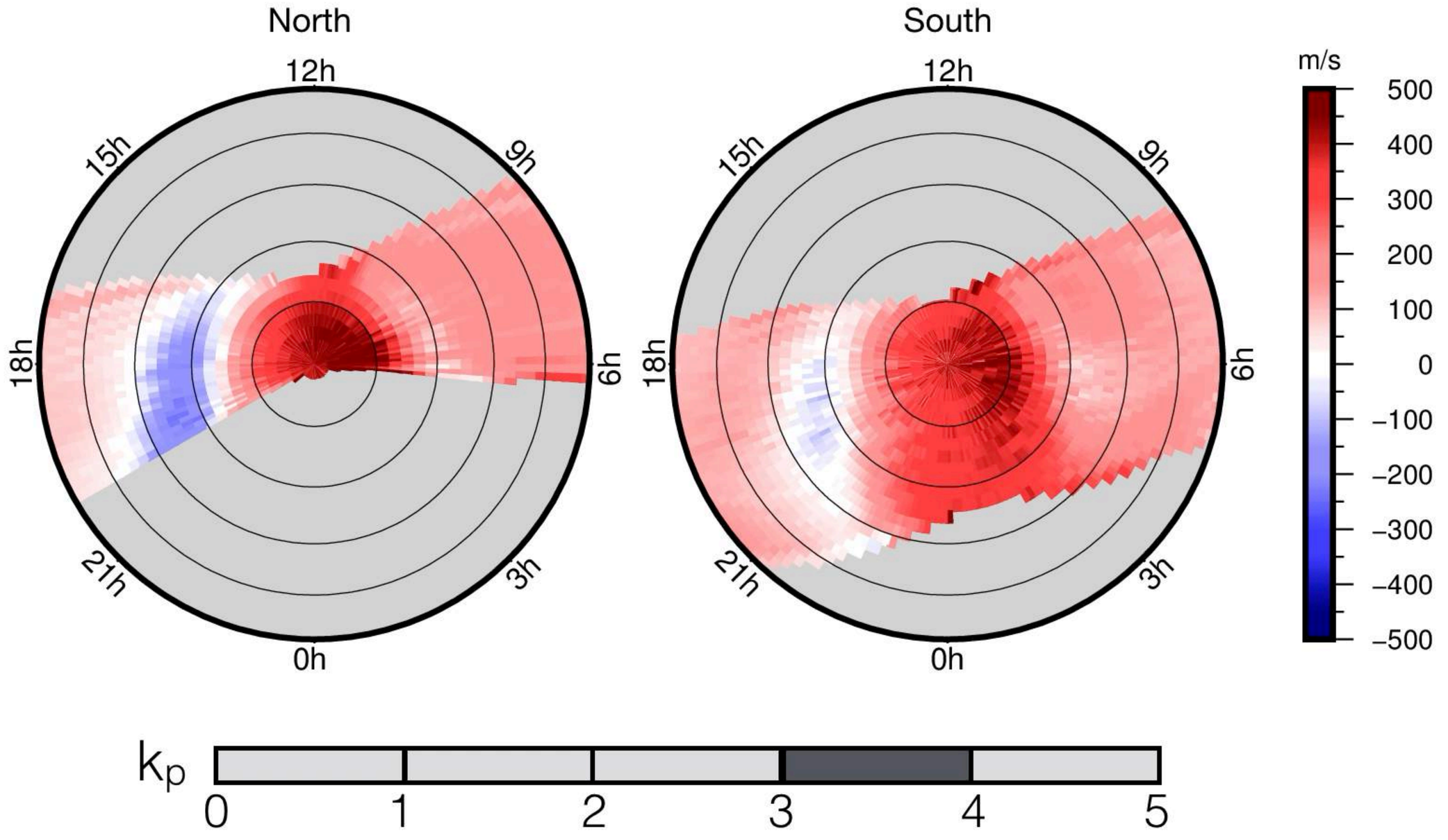





μA/m²
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Field−aligned current density
400 nT
IMF (10 nT)
g/km³
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Neutral air density at 470 km
2015−03−17 14:23


2015–03–18 00:09
μA/m²
Field–aligned current density
2.5
2.0
1.5
1.0
0.5
0.0
–0.5
–1.0
–1.5
–2.0
–2.5
IMF (10 nT)
400 nT
g/km³
Neutral air density at 470 km
3.0
2.5
2.0
1.5
1.0
0.5
0.0
UTC time
23:40
23:50
Swarm C
AMIE model
FAC density (μA/m²)
4
2
0
–2
–4
30
60
90
60
30
Latitude (deg)
UTC time
23:30
23:40
23:50
Swarm C
TIE-GCM model
Neutral density at 470 km (10⁻¹² kg/m³)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Dusk
Dawn
0
30
60
90
60
30
0
Latitude (deg)

GOCE anti-sunward wind, quasi-dipole magnetic latitude / magnetic solar time



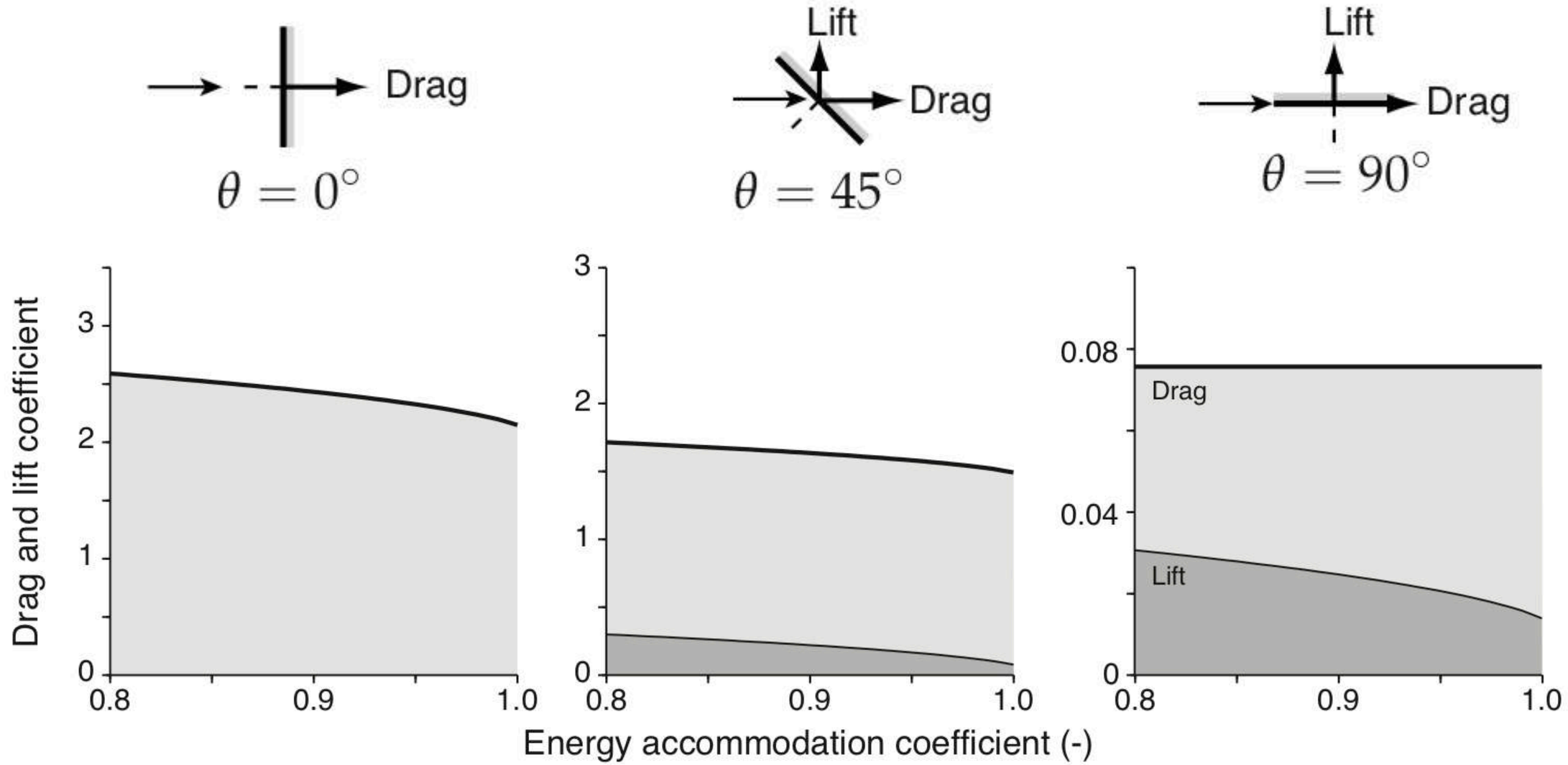
Uncertainty in satellite aerodynamics and the scale of the thermosphere

Uncertainty in satellite aerodynamics

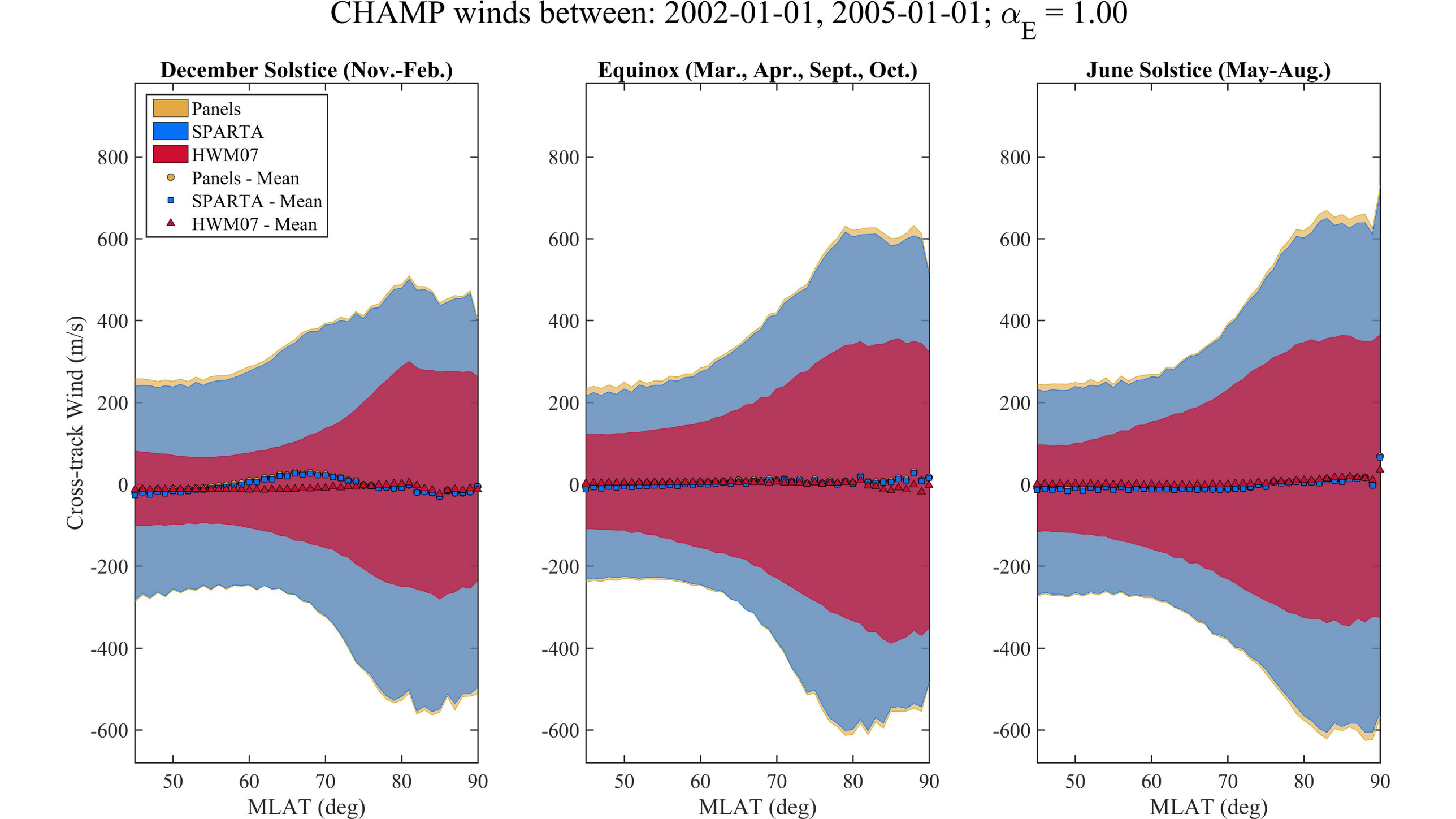
Energy flux accommodation coefficient

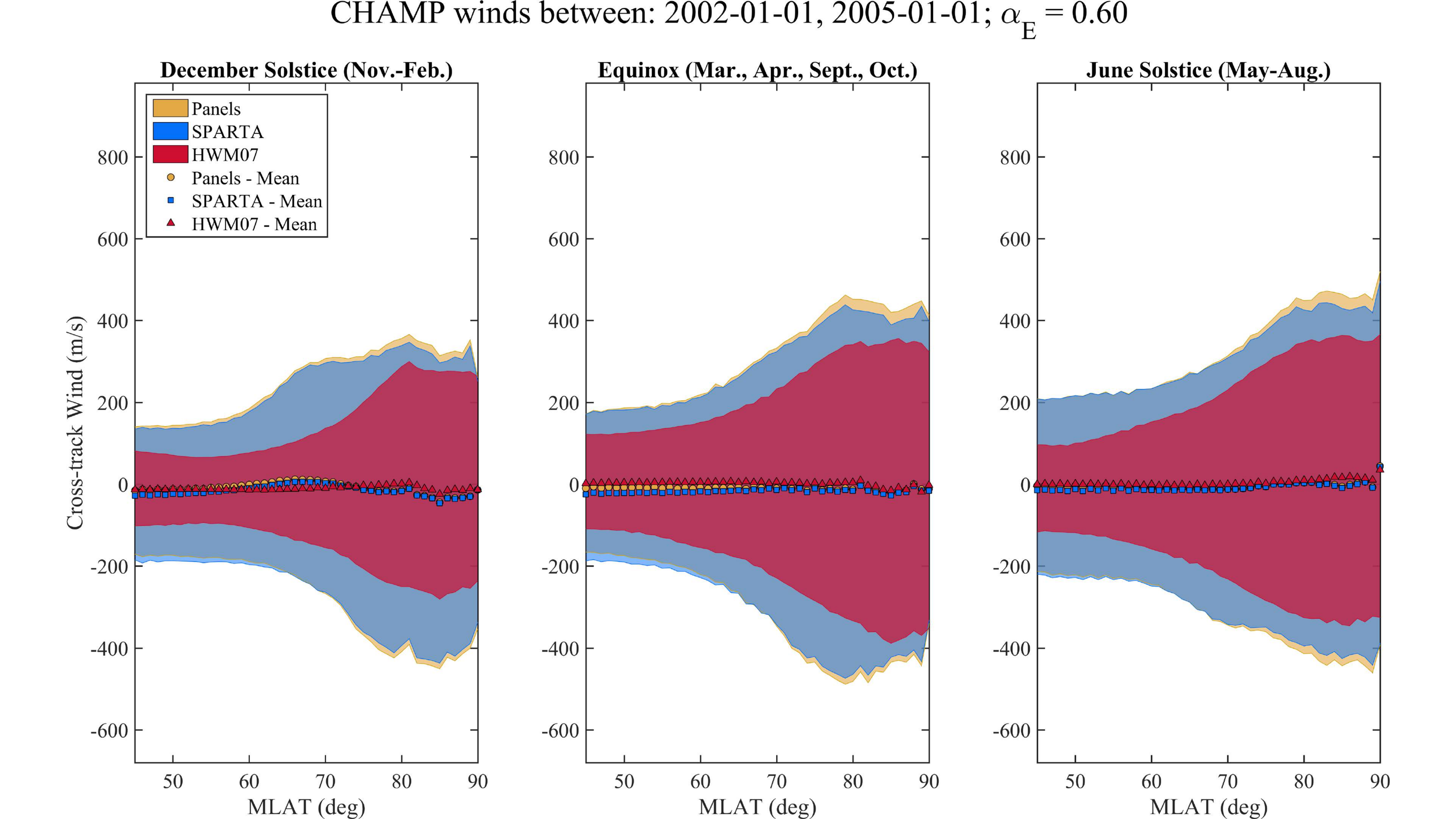
$$\alpha = \frac{T_i - T_r}{T_i - T_w}$$

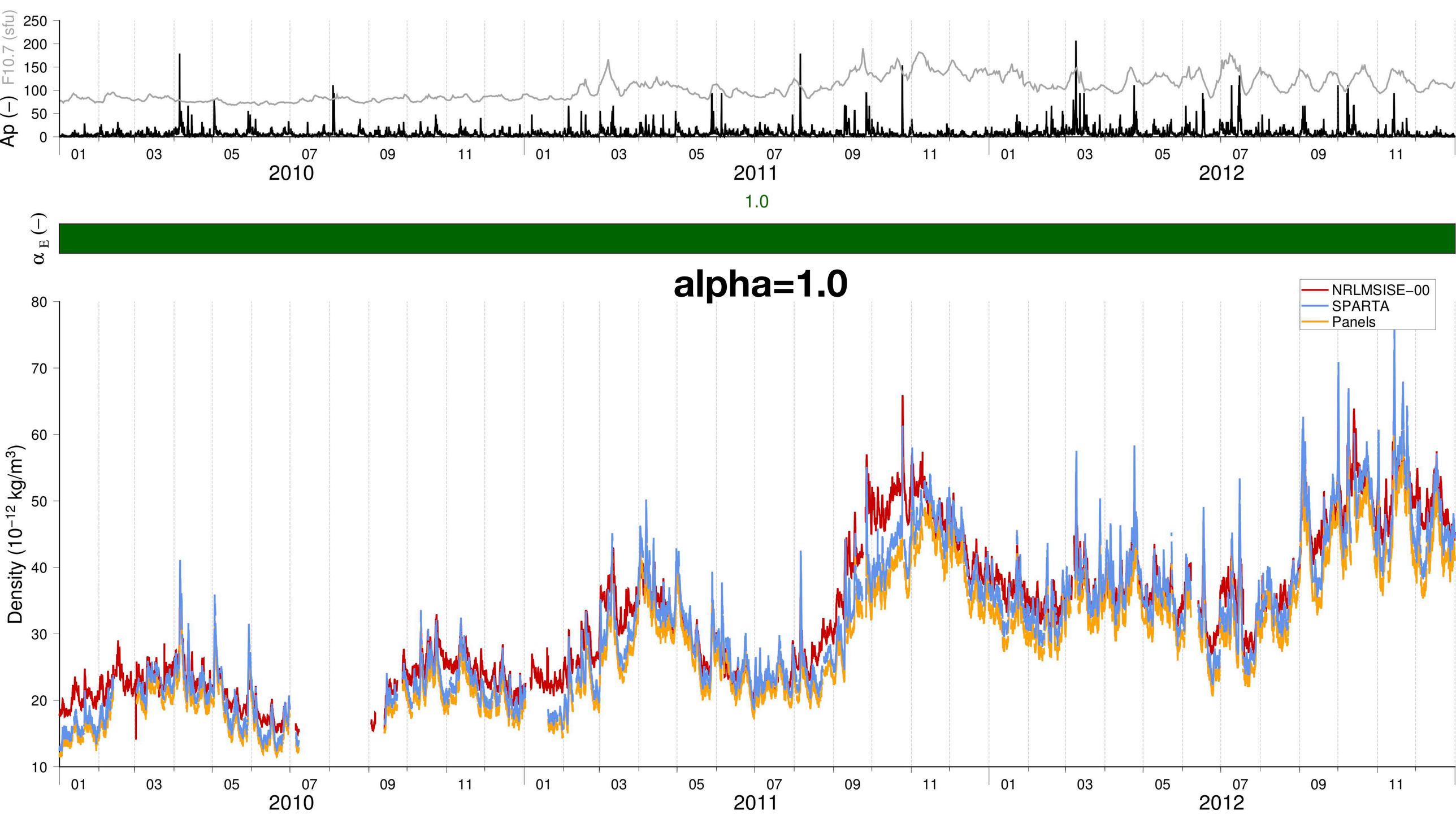
T temperature
i incoming particles
r reemitted particles
w wall

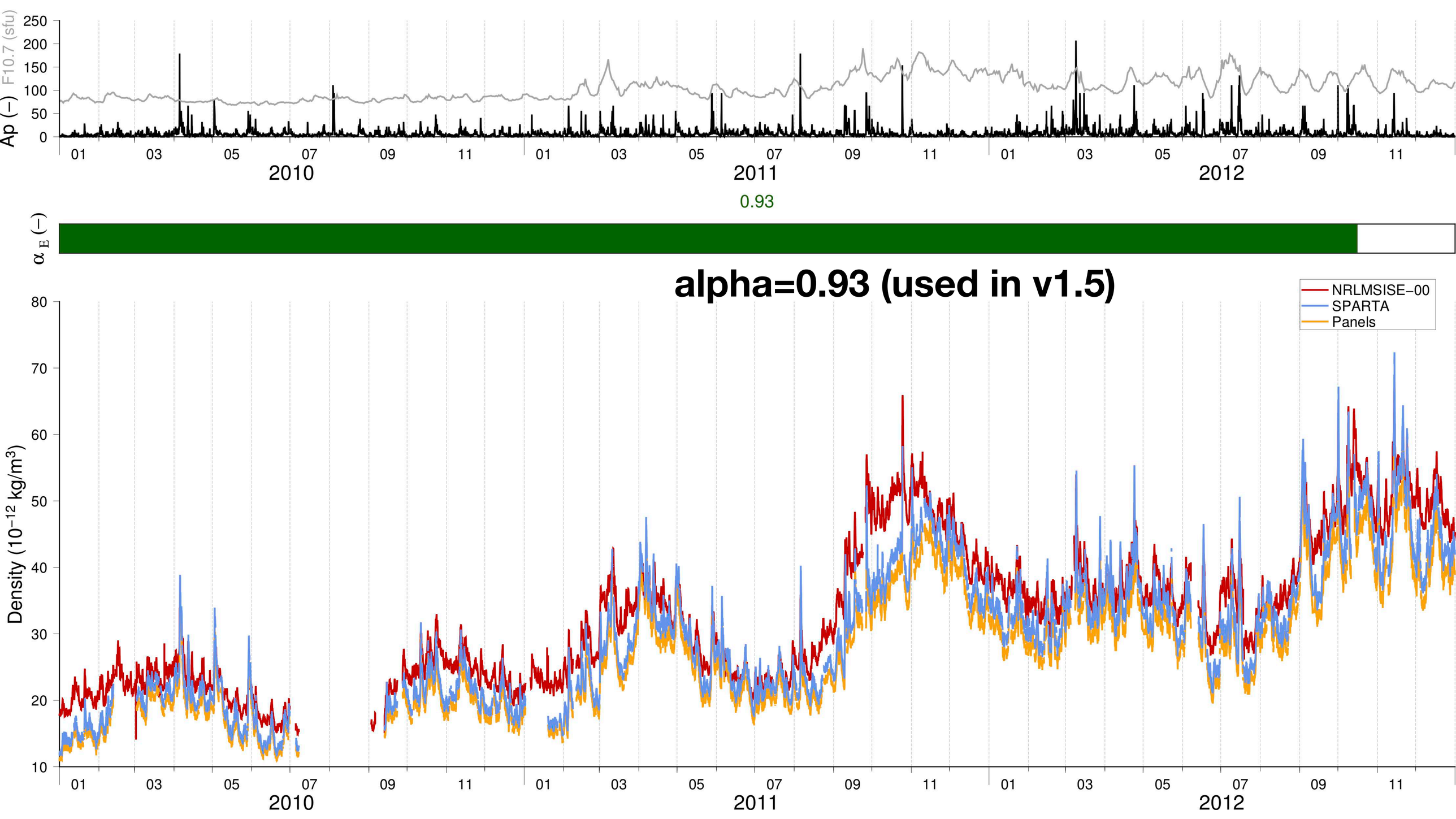


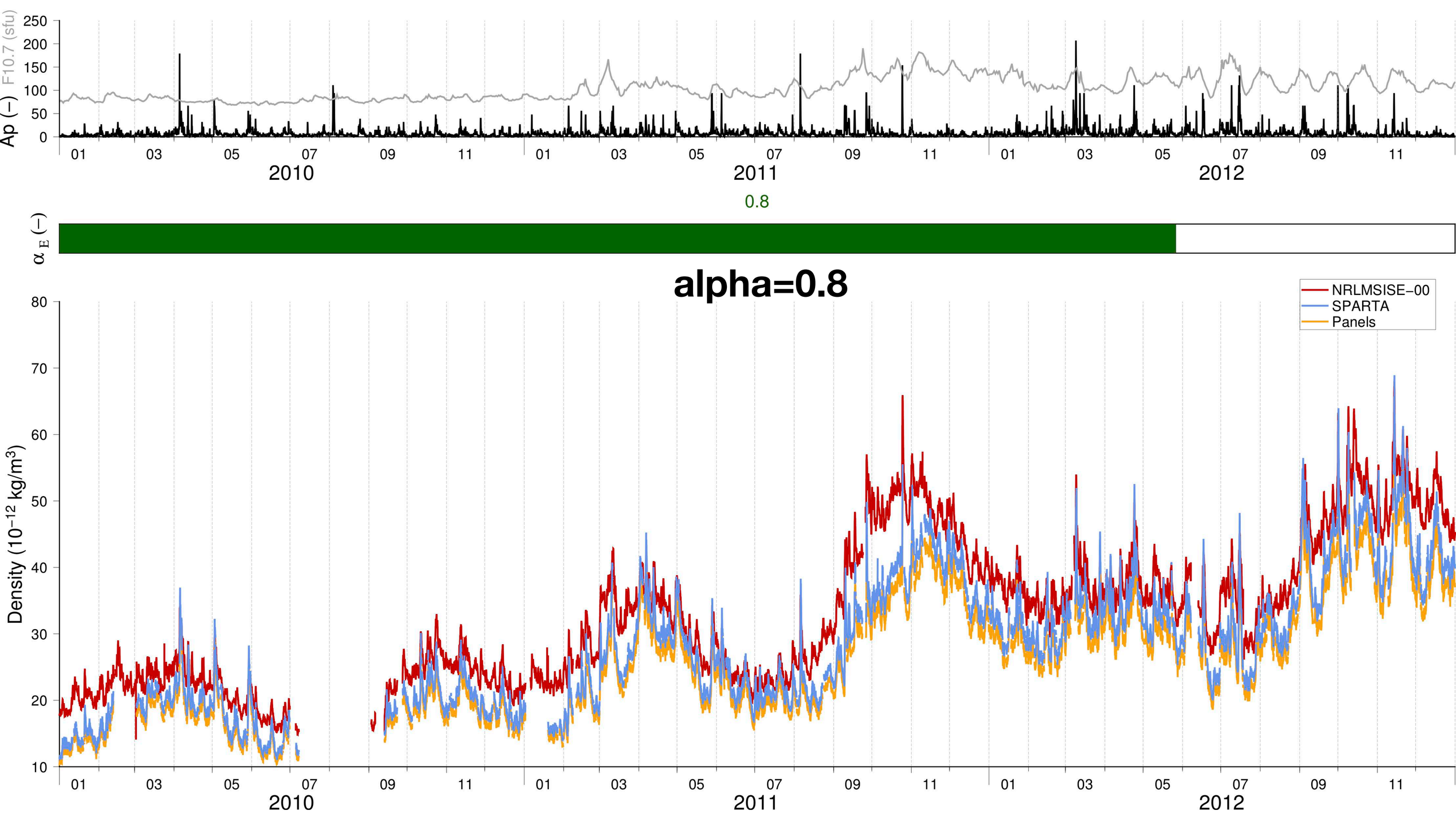
Doornbos, E. (2012). Thermospheric Density and Wind Determination from Satellite Dynamics. Berlin, Heidelberg: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-25129-0

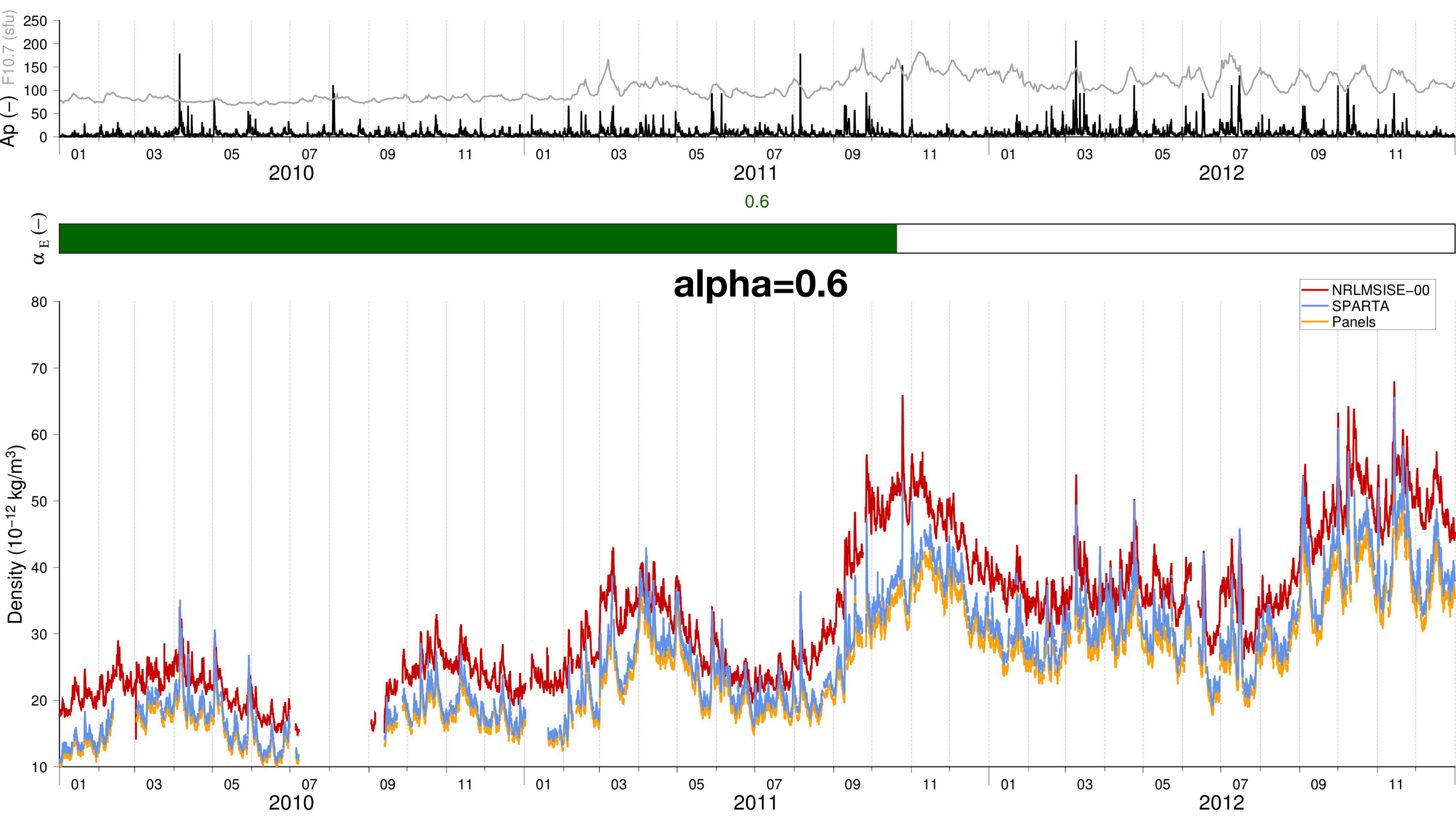

CHAMP winds between: 2002-01-01, 2005-01-01; α_E = 1.00
December Solstice (Nov.-Feb.)
Equinox (Mar., Apr., Sept., Oct.)
June Solstice (May-Aug.)
Panels
SPARTA
HWM07
Panels - Mean
SPARTA - Mean
HWM07 - Mean
Cross-track Wind (m/s)
800
600
400
200
0
-200
-400
-600
50
60
70
80
90
MLAT (deg)

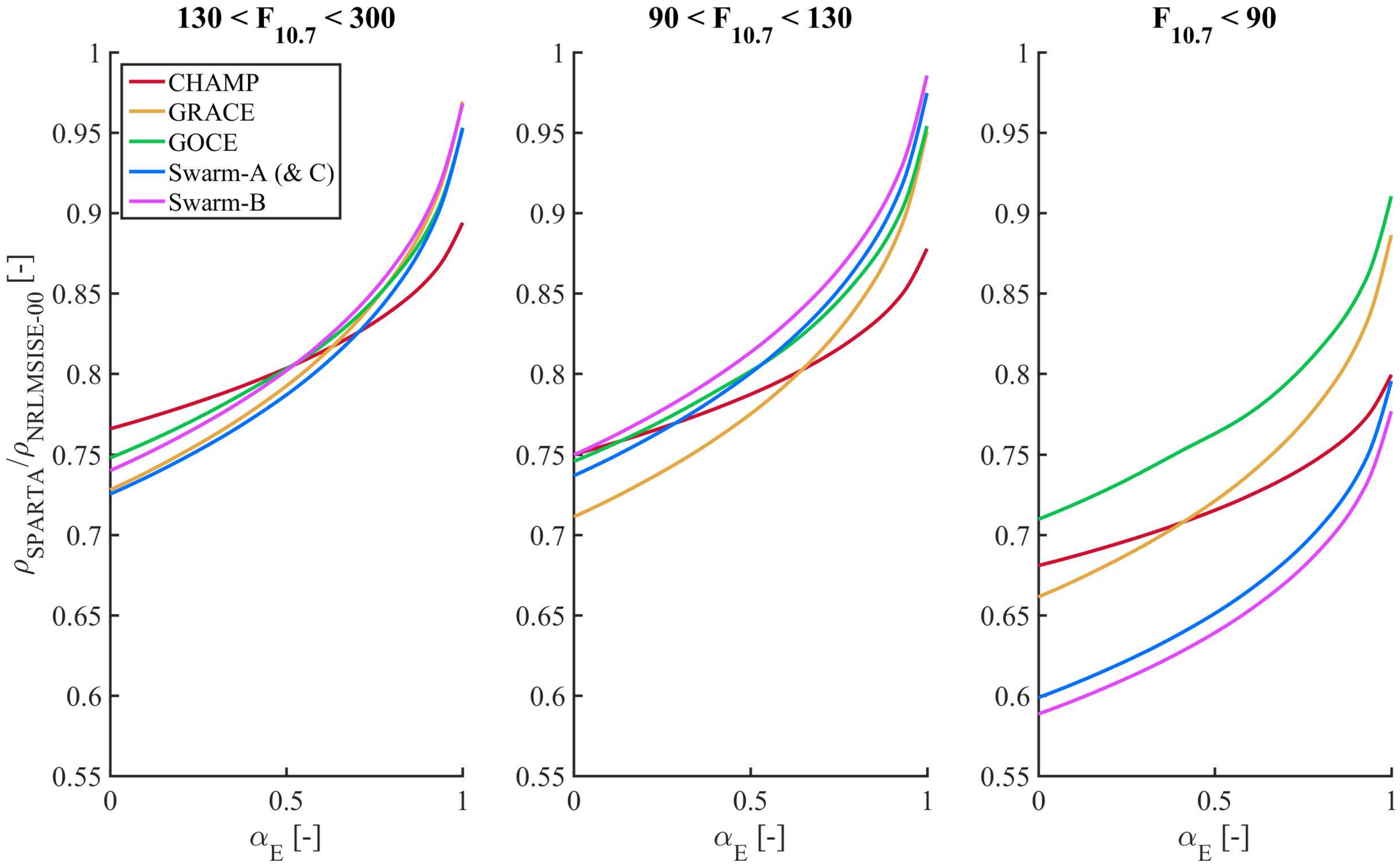

CHAMP winds between: 2002-01-01, 2005-01-01; $\alpha_E = 0.60$
December Solstice (Nov.-Feb.)
Equinox (Mar., Apr., Sept., Oct.)
June Solstice (May-Aug.)
Panels
SPARTA
HWM07
Panels - Mean
SPARTA - Mean
HWM07 - Mean
Cross-track Wind (m/s)
800
600
400
200
0
-200
-400
-600
50
60
70
80
90
MLAT (deg)

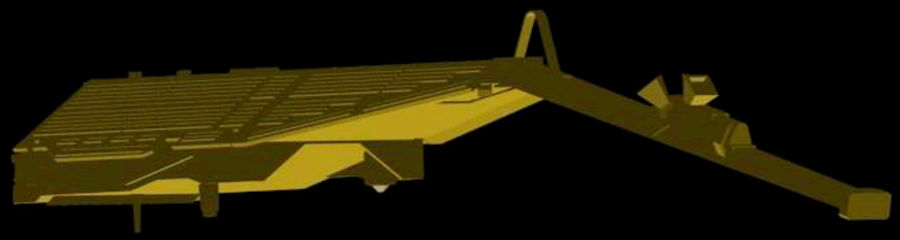

Ap (–)
F10.7 (sfu)
250
200
150
100
50
0
01
03
05
07
09
11
2010
2011
2012
1.0
α_E (–)
alpha=1.0
NRLMSISE–00
SPARTA
Panels
Density (10^{-12} kg/m^3)
80
70
60
50
40
30
20
10


Ap (–)
F10.7 (sfu)
250
200
150
100
50
0
01
03
05
07
09
11
2010
2011
2012
0.93
α_E (–)
alpha=0.93 (used in v1.5)
NRLMSISE–00
SPARTA
Panels
Density (10^{-12} kg/m^3)
80
70
60
50
40
30
20
10

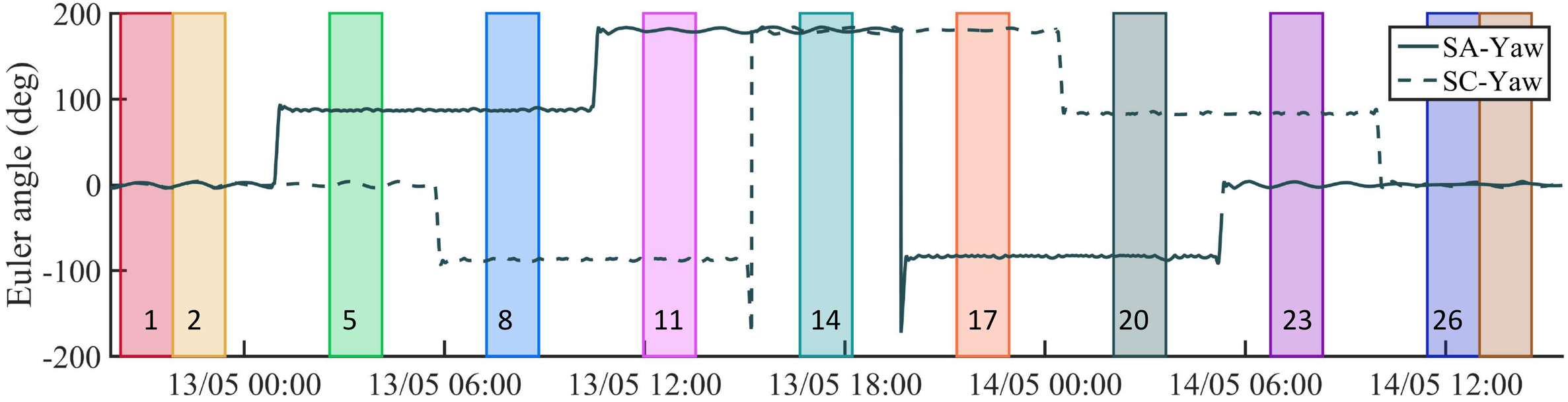

Ap (–)
F10.7 (sfu)
250
200
150
100
50
0
01
03
05
07
09
11
2010
2011
2012
0.8
α_E (–)
alpha=0.8
NRLMSISE–00
SPARTA
Panels
Density (10^{-12} kg/m^3)
80
70
60
50
40
30
20
10

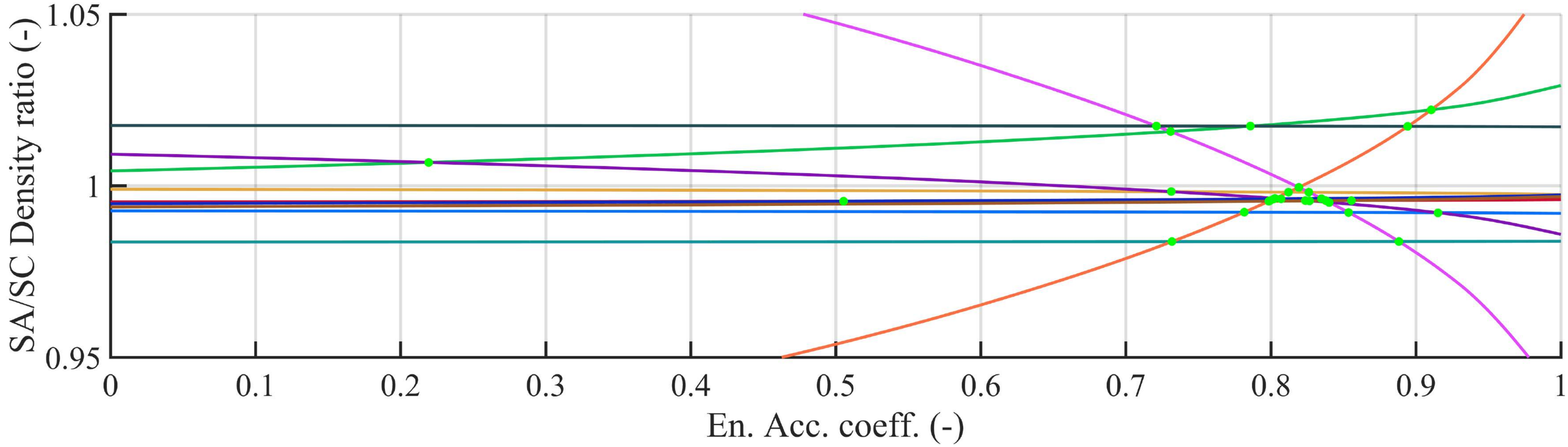

Ap (–)
F10.7 (sfu)
250
200
150
100
50
0
01
03
05
07
09
11
2010
2011
2012
0.6
α_E (–)
alpha=0.6
NRLMSISE–00
SPARTA
Panels
Density (10^{-12} kg/m^3)
80
70
60
50
40
30
20
10


130 < F10.7 < 300
90 < F10.7 < 130
F10.7 < 90
CHAMP
GRACE
GOCE
Swarm-A (& C)
Swarm-B
ρSPARTA/ρNRLMSISE-00 [-]
αE [-]
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0
0.5
1




Swarm A
orbit
Yaw
−180 0 180
18:00
May 12
00:00
06:00
May 13 12:00
18:00
00:00
06:00
May 14
12:00
18:00
Relative velocity
Radiation pressure model
ACCxPOD
Modelled aero alpha=1.0
Modelled aero alpha=0.8
Modelled aero alpha=0.6
Modelled aero alpha=0.4
Swarm C
Density (g/km3)
2.5
2.0
1.5
1.0
0.5
0.0
A C
MSIS
DNSxPOD-X
DNSxPOD-Y


Euler angle (deg)
200
100
0
-100
-200
SA-Yaw
SC-Yaw
1
2
5
8
11
14
17
20
23
26
13/05 00:00
13/05 06:00
13/05 12:00
13/05 18:00
14/05 00:00
14/05 06:00
14/05 12:00


SA/SC Density ratio (-)
1.05
1
0.95
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
En. Acc. coeff. (-)

What value of the accommodation coefficient to use?

- Further work ongoing by Gunther March, including Swarm manoeuvres, statistics on data from contemporaneous missions, etc.

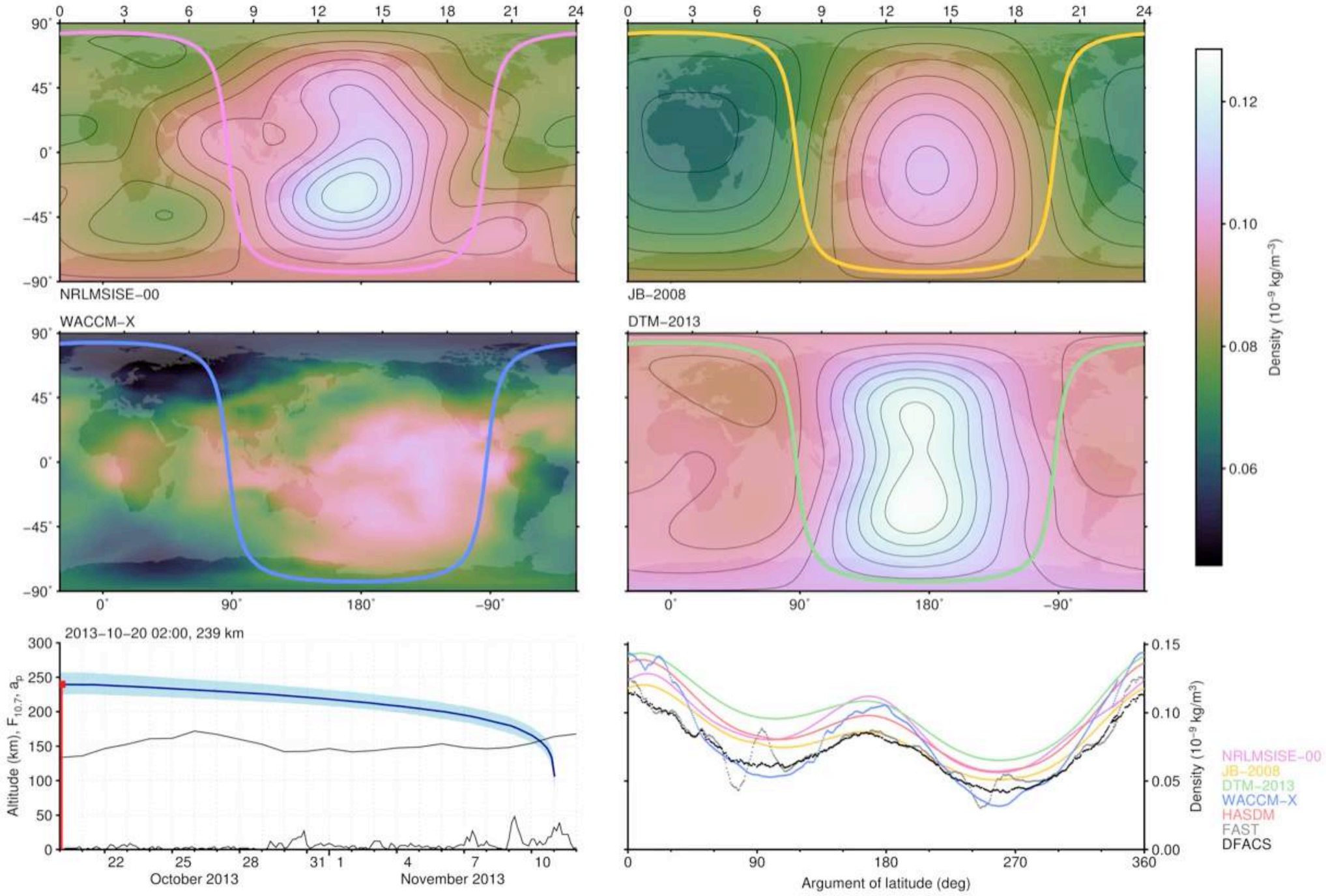
- Do we need to revisit our (currently very simple) assumptions for the temperatures of the incoming gas and satellite walls?

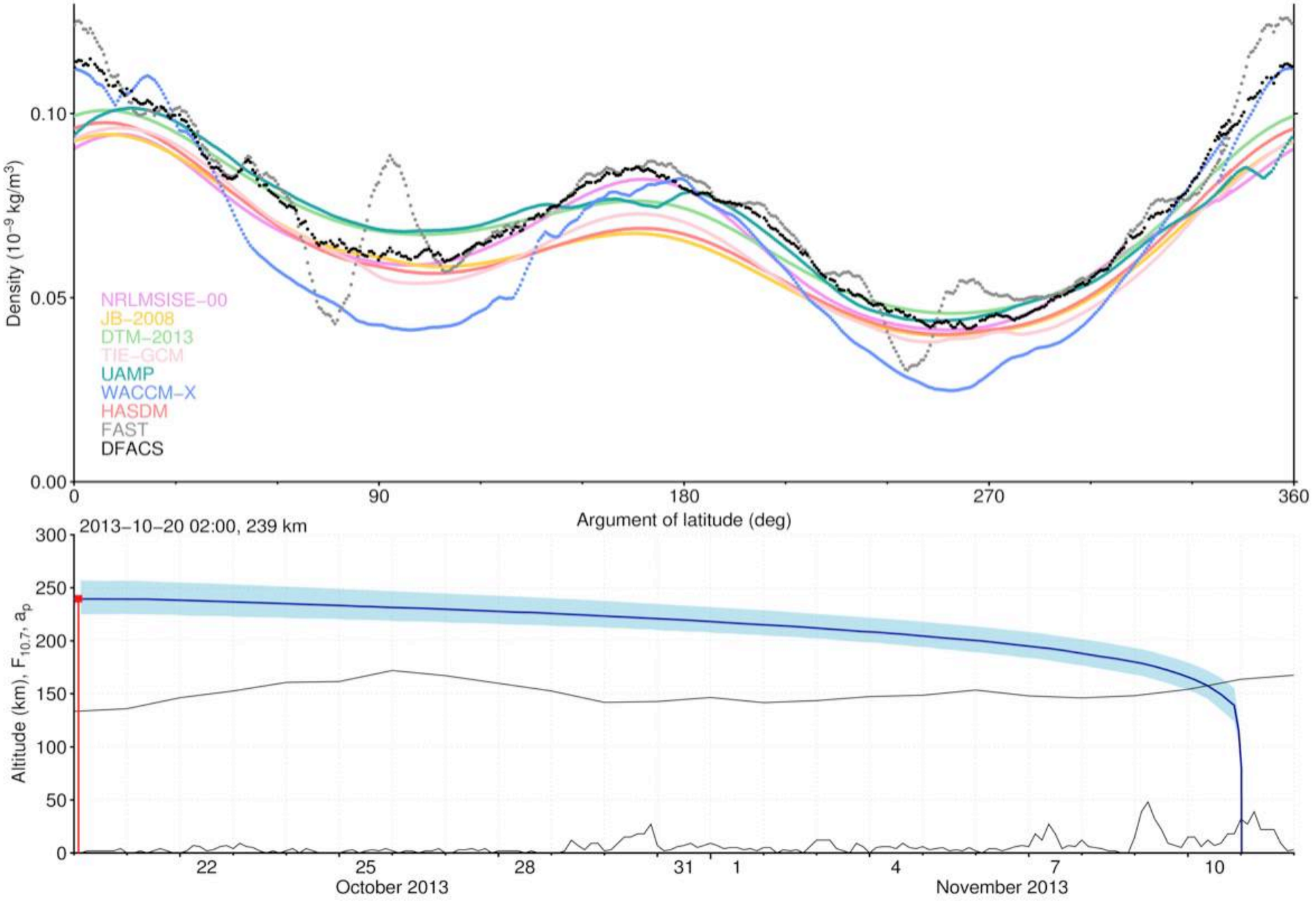
- What settings to use for GOCE v2.0 thermosphere data in the meantime? Perhaps provide two versions of the data?

  - One optimised for continuity of density observations

  - One optimised for improved consistency of horizontal wind observations with external data

GOCE re-entry special dataset

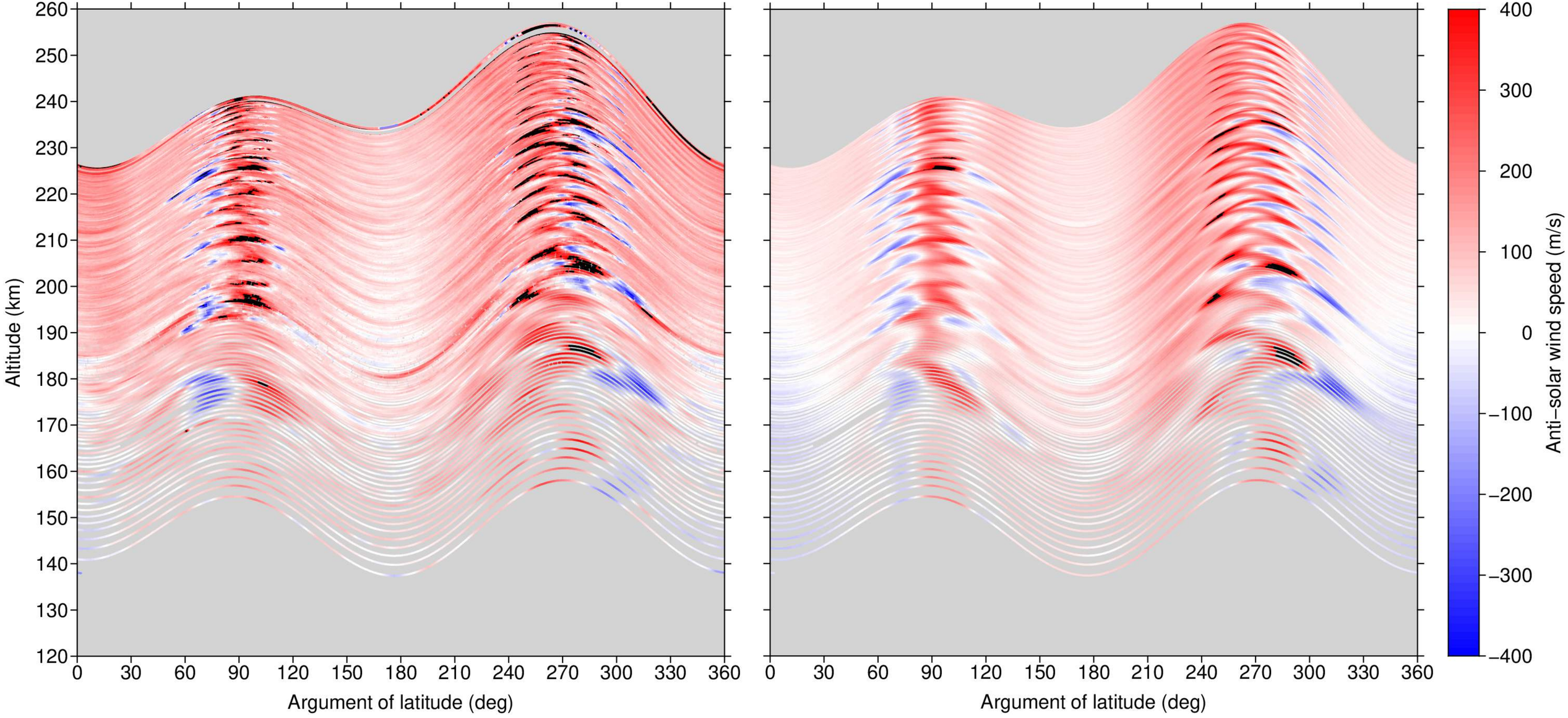

NRLMSISE-00
JB-2008
WACCM-X
DTM-2013
Density (10^{-9} kg/m^{-3})
2013-10-20 02:00, 239 km
Altitude (km), $F_{10.7}$, a_p
October 2013
November 2013
Density (10^{-9} kg/m^3)
Argument of latitude (deg)
NRLMSISE-00
JB-2008
DTM-2013
WACCM-X
HASDM
FAST
DFACS


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

TU Delft

GOCE wind data (patched GPS+ACC)

Equivalent TIE-GCM wind



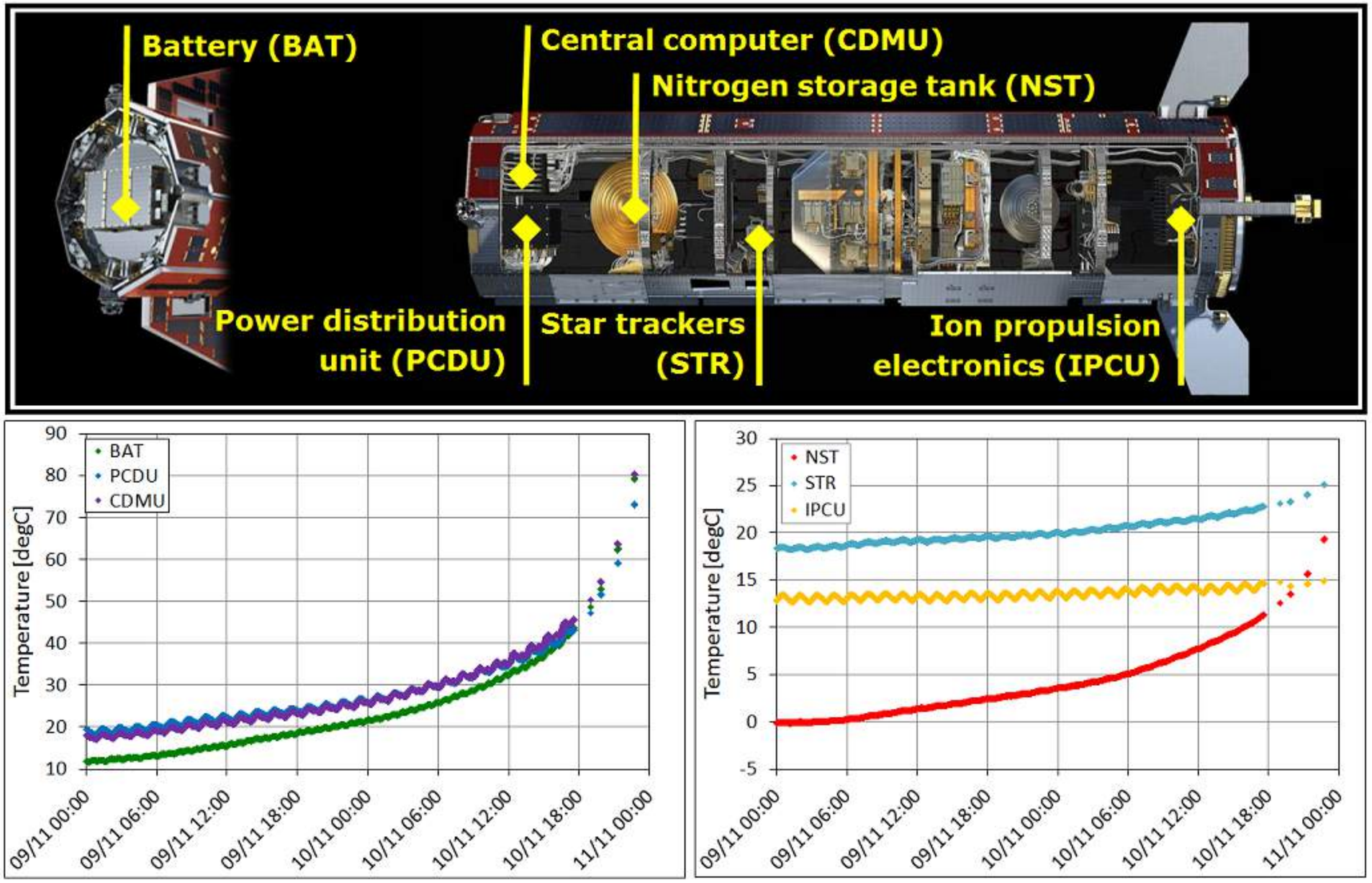
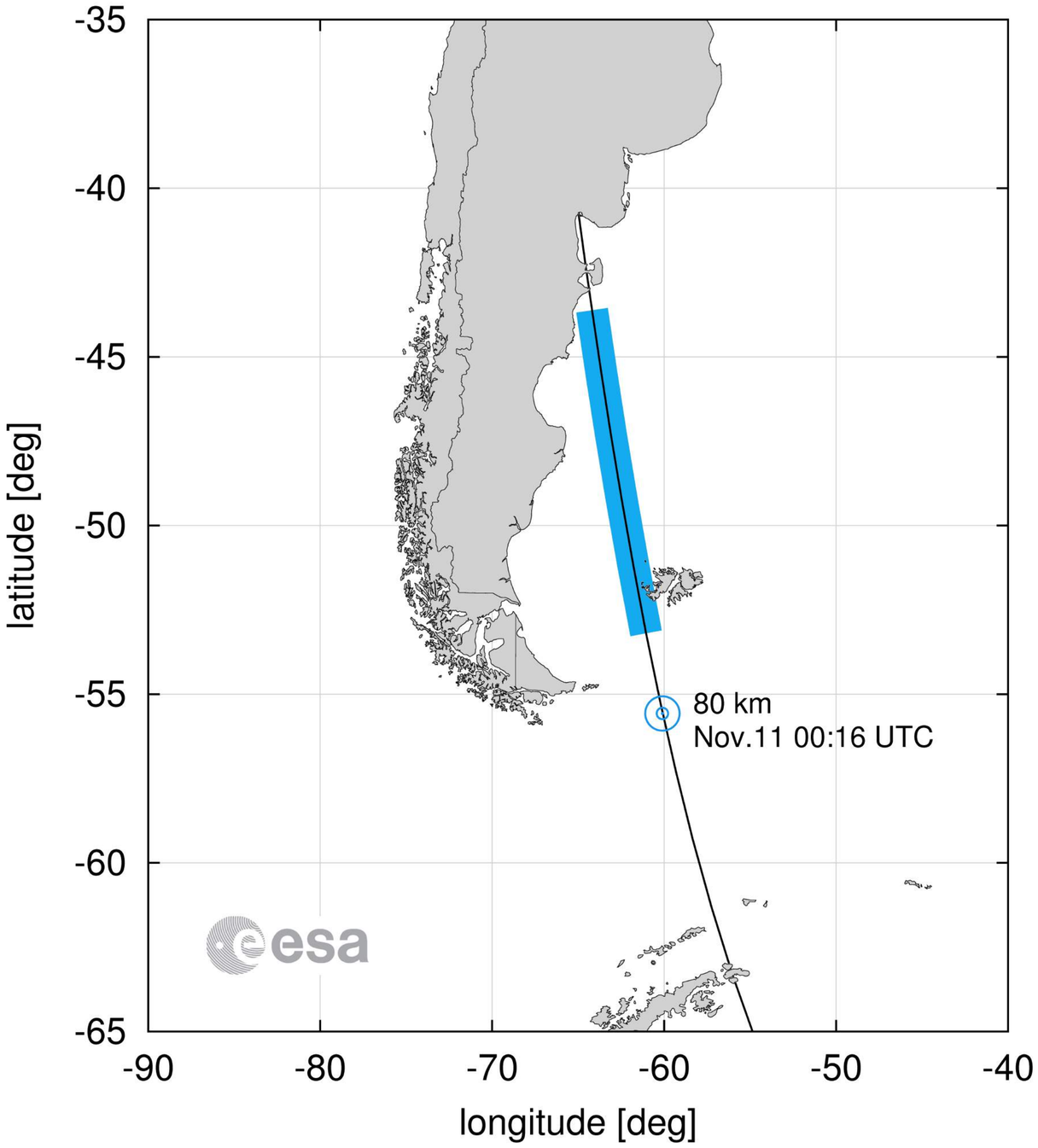


Figure 88: Evolution of temperatures in the last two days of flight, showing a major increase due to the S/C warm up caused by atmospheric friction, most pronounced for units close to the front of the S/C.

From ESA's GOCE end-of-mission operations report GO-RP-ESC-FS-6268


-35
-40
-45
-50
-55
-60
-65
latitude [deg]
-90
-80
-70
-60
-50
-40
longitude [deg]
80 km
Nov.11 00:16 UTC
esa

Conclusions

- Computing exact aerodynamic forces and torques on satellites is not a completely solved problem.
- There are strong indications from analysis of CHAMP, GOCE and Swarm density and wind data, that energy accommodation should be lower than previously thought.
- This has implications for the scale of the thermosphere. Thermosphere density is likely lower than indicated by current empirical models.
- For practical purposes (e.g. mission analysis), it is important to use satellite aerodynamic models and thermosphere models that are consistent with each other.

Visualisations and animations

- Some of the videos are available on https://vimeo.com/user2446191. Others will be added there when ready.

- Software used:

  - Generic Mapping Tools (GMT) for 2D graphs, and map projections (gmt.soest.hawaii.edu)

  - Blender for 3D rendering (www.blender.org)

  - Apple Motion for compositing and 2D animation (www.apple.com/final-cut-pro/motion/)

  - Python for data (pre)processing